Optimal Scheduling of a Residential Energy Storage Device in Multi-Carrier Energy Systems

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***Abstract*—These days, the use of multi-carrier energy systems to supply the electrical and thermal consumption of residential buildings has increased. This paper presents an initial approach for hourly scheduling of a multi-carrier energy system for a residential house including photovoltaic panels, battery, heat pump and gas boiler. The system is modelled as an energy hub in which a coupling matrix is defined to link input energy carriers to the output energy carriers while minimizing the operational cost. In order to evaluate the proposed method, three different scenarios are presented and the results are compared together. The simulation results show the optimal scheduling of units, specially the battery, not only decrease the operational cost of the energy hub, but also reduce the dependability on the grid and leads to increase self-consumption.**

***Index Terms*—battery scheduling, energy hub, multi-carrier energy systems.**

Nomenclature

E_{in}^{grid}	electricity imported from grid
E_{in}^{solar}	energy generated by solar irradiation
E_{in}^{gas}	imported gas to the building
E_{out}^{ed}	electrical demand
E_{grid}^{PV}	electricity injected to the grid
E_{out}^{td}	thermal consumption
Δt	time intervals
P	Price in euro/kWh
β	Dispatch factor
η	efficiency
$\alpha_{c/d}$	Charge/discharge factor
ed	Electrical demand
td	Thermal demand
b	battery
HP	Heat pump

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I. Introduction

According to the EU 20-20-20 targets [1], it is required to increase the share of energy consumption that is produced by renewable energy sources (RESs), decrease greenhouse gas emission and increase energy efficiency. Possible opponent is to couple different energy carriers, known as multi-carrier energy systems (MCESs). This has recently received increasing attention as they represent a valuable way to operate RESs and make more efficient use of energy carriers [2], [3]. The application and usage of MCESs in buildings, such as supply of electricity and heating, are rapidly growing due to bellowed main advantages [4], [5]:

1) Synergy effects: the effect of combined energy carriers' system is greater than the sum of their separate effects.
2) increased reliability: supplying the demand is not depending on only one single infrastructure.
3) flexibility of supply: possibility to switch from one energy carrier to other energy carrier in order to supply demand.

However due to high number of design variables and combined infrastructures, optimal operation of MCES is a complex decision [6] which requires to be investigated. On the other hand, the mismatch between energy supply and energy demand becomes a challenge in MCESs, especially when it has been combined with renewable energy units. To overcome the latter challenge, different energy storage devices, e.g. battery and thermal energy storage can be used which add more complexity to the systems in terms of finding optimal scheduling.

Some researches have been investigated in order to tackle the above problems. Diekerhof *et al*. [7] , investigate on the optimal operation of battery and thermal energy storage for residential customers which leads to decrease the operational cost while taking the uncertainty into account by applying a two-stage stochastic optimization. In a similar way, Good *et al*. [8], maximize the flexibility at district level in multi-energy environment by utilizing stochastic optimization.

This paper proposes an approach to optimal scheduling of battery to meet the energy for electrical and thermal demand. It is important to mention that the focus of this paper is to find the optimal scheduling of battery and other units, such as gas boiler and heat pumps, which leads to minimize household operational costs. The investment issues and possible financial incomes to provide ancillary services for the network are out of scope of this paper.

The rest of the paper is organised as follows: First, the mathematical model of a residential energy hub and a coupling matrix while PV, battery, heat pump and gas boiler are installed are defined in Section II. Then, in Section III the optimization model including objective and required constraints, is described. To evaluate our approach, the proposed method is applied to a representative Belgian household and the result is discussed in Section IV. Finally, the paper ends with a conclusion and some suggestions for future work in Section V.

II. Energy Hub for Residential Building Modeling

The "Energy hub" concept [9], [10] is a black box model that converts the input energy carriers to the output energy carriers of the building via coupling matrix (D). An energy hub enables to model complex systems and match the supply of different energy carriers with the demand of various energy carriers [6]. In this paper energy hub is modelled as follows:

Fig.1 illustrates the investigated energy hub for this case study. It is assumed that there are various energy convertors (PV- convert solar radiation to electricity-, heat pump - produce heat by consuming electricity- and gas boiler – convert natural gas to heat-) in order to meet the energy demand of the residential customer. Moreover, in order to compensate the mismatch between PV generation and energy consumption of a building, a battery is also included in the energy hub. The goal of modelling is to determine optimal:

1) gas consumption
2) interaction with grid in terms of consumption and injection
3) battery charge and discharge
4) optimal switching from electricity to gas consumption in order to supply thermal demand

While the total electrical and thermal demand are given for each time interval.

In order to mathematically model the energy hub, the input and output matrixes can be defined as (1) and (2) respectively:

$$E_{in}(\Delta t) = \left[E_{in}^{grid}(\Delta t) \quad E_{in}^{solar}(\Delta t) \quad E_{in}^{gas}(\Delta t) \right]^T \tag{1}$$

$$E_{out}(\Delta t) = \left[E_{out}^{ed}(\Delta t) \quad E_{out}^{td}(\Delta t) \right]^T \tag{2}$$

Where T stands for transposed matrix in (1) and (2). Then, for each time intervals matrix D can be written as (3):

$$E_{in}(\Delta t) = D(\Delta t) \times E_{out}(\Delta t) \tag{3}$$

According to fig.1. and proposed energy hub, coupling matrix is defined in (4):

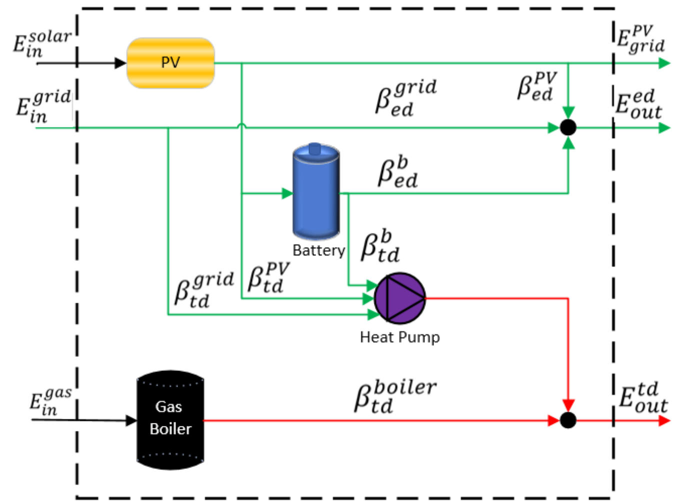

Fig. 1. Schematic of the considered residential energy hub

$$D(\Delta t) = \begin{bmatrix} A & B \\ C & F \\ 0 & G \end{bmatrix} \tag{4}$$

Where:

$$A = \beta_{ed}^{grid}(\Delta t) \tag{4.a}$$

$$B = \frac{\beta_{td}^{grid}(\Delta t)}{\eta_{HP}} \tag{4.b}$$

$$C = \frac{\beta_{ed}^{PV}(\Delta t)}{\eta_{PV}} + \frac{\alpha_d(\Delta t)}{\eta_b}\beta_{ed}^{b}(\Delta t) \tag{4.c}$$

$$F = \frac{\beta_{td}^{PV}(\Delta t)}{\eta_{PV} \times \eta_{HP}} + \frac{\alpha_d(\Delta t)}{\eta_b \times \eta_{HP}}\beta_{td}^{b}(\Delta t) \tag{4.d}$$

$$G = \frac{\beta_{td}^{boiler}(\Delta t)}{\eta_{boiler}} \tag{4.e}$$

These dispatch factors β describe the amount of output energy carriers which is supply by a particular energy unit during each time step. For instance, there are three different ways to supply electrical demand and β_{ed}^{PV} is the factor for the electricity which is supplied by PV production. It is important to mention that β can be any value between 0 and 1 and for all output energy carriers (5) and (6) must be verified.

$$\beta_{ed}^{grid}(\Delta t) + \beta_{ed}^{PV}(\Delta t) + \beta_{ed}^{b}(\Delta t) = 1 \tag{5}$$

$$\beta_{td}^{grid}(\Delta t) + \beta_{td}^{PV}(\Delta t) + \beta_{td}^{b}(\Delta t) + \beta_{td}^{boiler}(\Delta t) = 1 \tag{6}$$

III. Optimal Scheduling of Units

As discussed in Section I, due to high number of design variables and coupling different energy infrastructures optimal

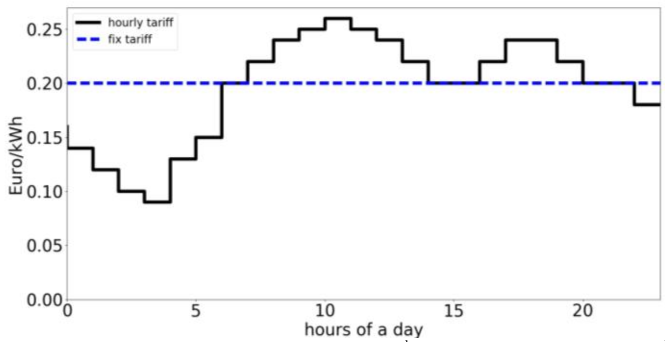

Fig. 2. Dynamic (hourly) price in 1st and 2nd scenario VS fix price for 3rd scenario

operation of such systems need more studies. The energy hub modeling and optimization become more complex when energy storage devices such as battery, are included to compensate the mismatch between PV production and household's demand.

Therefore, in order to find the optimal scheduling for each unit proposed in fig.1, all factors of β are decision variables of optimization problem which lead to minimize the operational cost. It is assumed that the total demand for electricity and heating, energy carriers' price and total PV production are given to the problem. So the output of optimization should be the amount of energy which is transferred between each two points of energy hub.

A. Objective function

In order to obtain the optimal scheduling of the battery, the system is modelled as a mixed-integer quadratic program. This program can minimize the operational cost, which is defined by (7):

$$\min \sum_{\Delta t} \overbrace{\left[\beta_{ed}^{grid}(\Delta t)\times E_{out}^{ed}(\Delta t)+\frac{\beta_{td}^{grid}(\Delta t)}{\eta_{HP}}\times E_{out}^{td}(\Delta t)\right]\times P_{buy}(\Delta t)}^{1} \qquad (7)$$
$$\underbrace{\frac{\beta_{td}^{boiler}(\Delta t)}{\eta_{boiler}}\times E_{out}^{td}(\Delta t)\times \mathrm{P}_{gas}}_{2}\underbrace{-E_{grid}^{Pv}\times P_{sell}}_{3}$$

The first part of (1) belongs to the cost of electricity which is bought from grid to meet both electrical and thermal demand. The expense for gas consumption in order to supply the thermal demand is included in the second part of (7). It is assumed that the customer can sell the extra PV production to the grid, so the third part of (3) express the possibility to earn some money by selling electricity to the grid.

B. Units' constraints

Above from (1-6) which are considered as the constraints for optimization problem, nominal energy output for gas boiler, heat pump and battery discharge are taken into account.

To model the battery, its State of Charge (SoC) is used. SoC can be defined as (8):

$$SoC(\Delta t)=SoC(\Delta t-1)+\frac{\eta_{charge}\times E_{charge}(\Delta t)}{capacity}-\frac{E_{discharge}(\Delta t)}{\eta_{discharge}\times capacity} \qquad (8)$$

Where E_{charge} means the total energy transferred from PV to charge the battery and $E_{discharge}$ is the total energy delivered by the battery to meet the electrical and thermal demand is $E_{discharge}$ of battery.

For each time step, SoC should remain whithin a certain interval. In other words, for a battery it is not possible to charge when its SoC is above SoC_{max} or discharge when SoC is below SoC_{min}:

$$SoC_{\min}\le SoC(\Delta t)\le SoC_{\max} \qquad (9)$$

Moreover, for battery it is not possible to charge and discharge simultaneously. In this case, two binary parameters are defined:

$$\alpha_c(\Delta t)\times\alpha_d(\Delta t)=0 \qquad (10)$$

IV. Case Study

A single house includes an installed battery with capacity 40 kWh, efficiency charge and discharge 90%, maximum SoC is 90% and minimum SoC is 20%. The nominal energy output for the heat pump, gas boiler and battery discharge are set to 14 kWh, 35 kWh and 8 kWh, respectively.

The hourly data for a period of 350 days obtained from two different projects: Linear (Local Intelligent Networks and Energy Active Regions) project [11] and OpenIDEAS (Integrated District Energy Assessment Simulations) [12]. Linear provides electrical demand and OpenIDEAS represents the thermal demand and PV production for a Belgian residential customer.

In this paper the below assumptions are taken into account:

1) The PV production, building consumption (both electricity and thermal), and the price of energy carriers are available in advance to optimize hourly operation of the energy hub.
2) According to [13], in order to reduce the dependency of residential customers to the grid, in this paper the battery can only charge by PV.
3) The efficiency of boiler is set to 80%, while in reality the efficiency can be varied according to the energy output.
4) In order to give more incentive to customer to increase self-consumption instead of injecting to the grid, the price for injecting electricity is set to 0.15 Euro/kWh.
5) Since in reality, there is not too many changes in the price of gas for residential customers in Belgium, here it is assumed that customer have a fix contract for using gas at price of 0.075 Euro/kWh.

In order to determine the effect of battery and the effect of dynamic pricing on energy hub, three different scenarios are defined. The first scenario describes the energy hub without battery while customer receives dynamic pricing. In scenario two and three, it is assumed that energy hub includes battery and customer can sign a contract to receive dynamic pricing (the second scenario) or fixed price (the third scenario. Fig.2 illustrates both fixed and dynamic price to buy electricity from grid over one day (24 hours). It is assumed that the signal for price repeats for all the other days.

In order to visualize the result, two sample days over 350 days are chosen. The day when the daily PV energy production reaches to the highest amount for that period and the other day with maximum thermal demand over these 350 days.

Fig.3. shows and compares the simulation results for the first scenario when there is no battery inside the energy hub (fig.3. a, b) with the second scenario when energy hub includes battery and can store electricity (fig.3. c, d). As fig.3. a. illustrates, from morning till afternoon, the energy hub continuously injected the extra PV production to the grid while earlier in the morning and during night when there is no PV production it consumes electricity from grid. However, for the same day (PV production max), fig.3. c. indicates using the battery leads to significantly decrease in interaction with grid. Only late at night and earlier morning when the price of electricity is low, energy hub buys electricity from grid. Also by comparing fig.3 b. and d. it can be concluded that applying the battery has no direct effects on gas consumption for the day with maximum thermal consumption; although, in that particular day some part of thermal demand is supplied by heat pump which is consumed electricity. Therefore, it can explain the differences between grid consumption during noon. In Fig.3. d., to avoid buying electricity in high price to meet the thermal demand (since heat pump reaches to its nominal energy output), battery will be discharge while in scenario one this energy is supplied by grid.

Generally, it can be concluded that using a battery in an energy hub, besides decreasing operational cost, can lead to decrease the interaction with grid.

Fig. 4. compares the results of the second scenario in which customers receive dynamic prices, with the third scenario in which the price of electricity is fixed. In order to see the effect of dynamic pricing (fig.4. a. and c.), the battery should be charged when the price of electricity is low and there is some PV production, then during time of high electricity price battery should be discharged to avoid buying electricity and increasing the operational cost. This issue can be seen especially by comparing fig.4. b. and d., where battery discharged to compensate the gas boiler to supply thermal demand when the electricity price is high.

Moreover, by comparing the total operation cost, it is determined that the second scenario lead to lowest operational cost for this proposed energy hub, while the first scenario leads to the highest cost.

V. Conclusion

This paper proposed an initial approach to optimally schedule an energy hub includes PV, heat pump, battery and gas boiler to meet the electrical and thermal demand. The goal of this paper was to minimize the total operational cost during 350 days and to evaluate the proposed method a simulation was applied to a representative Belgian residential building

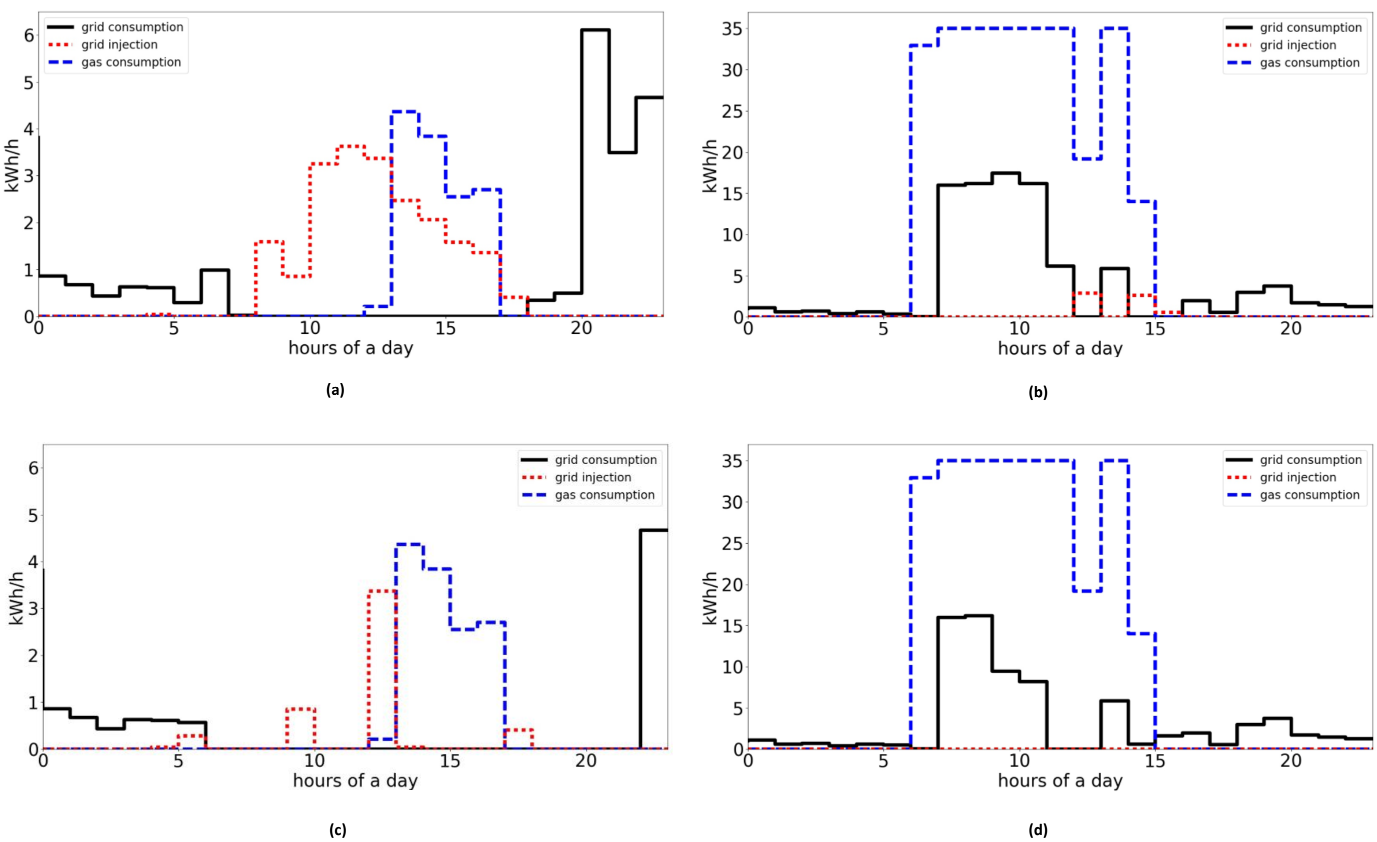

Fig. 3. Grid interaction (consumption and injection) and gas consumption, (a) data for the first scenario (no battery) in day with maximum PV generation. (b) data for the first scenario (no battery) in day with maximum thermal consumption. (c) data for the second scenario (with battery) in day with maximum PV generation. (d) data for the second scenario (with battery) in day with maximum thermal demand.

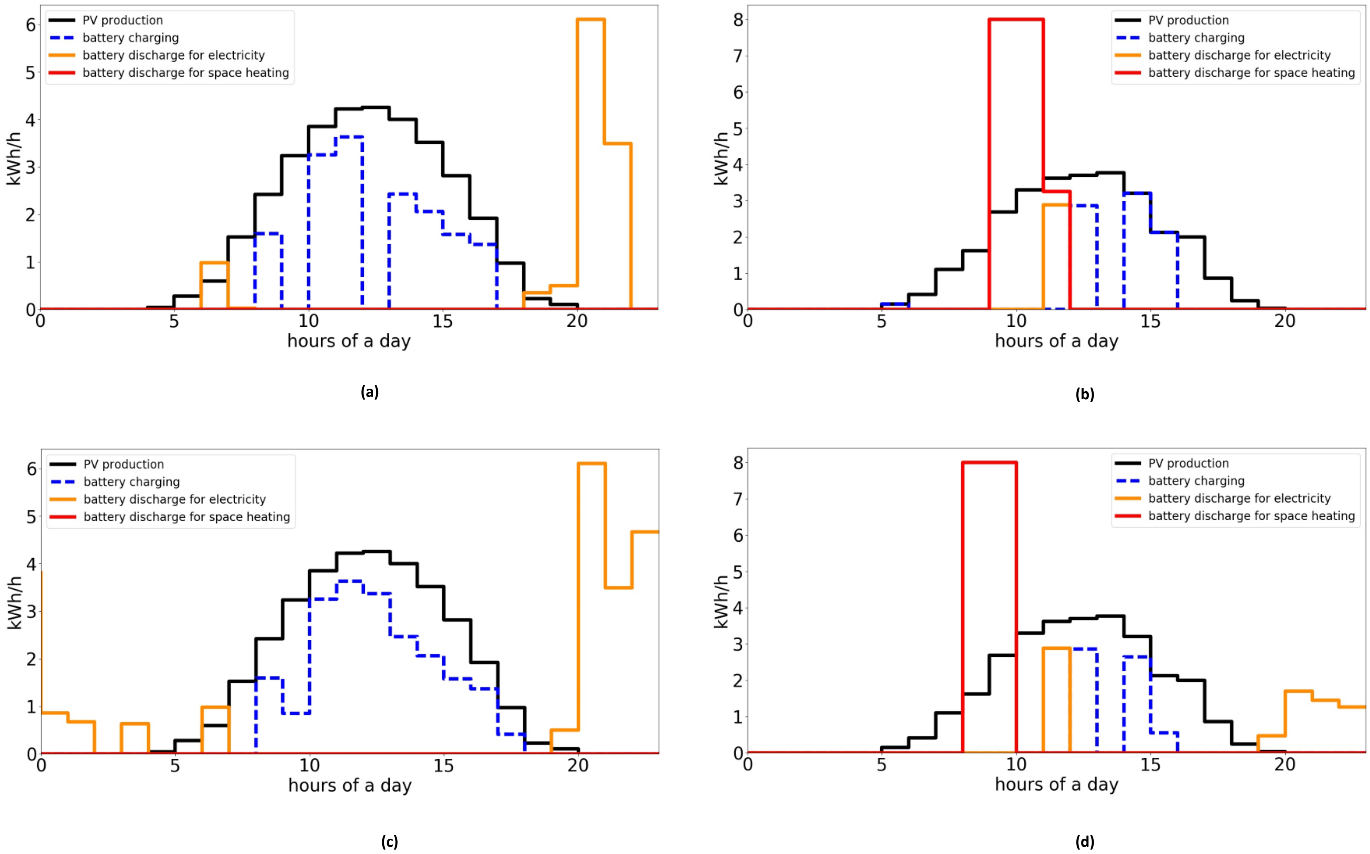

Fig. 4. PV production, battery charging from PV and battery discharging (for both electricity and convert to heat via heat pump), (a) data for the second scenario (dynamic price) in day with maximum PV generation. (b) data for the second scenario in day with maximum thermal consumption. (c) data for the third scenario (fixed price) in day with maximum PV generation. (d) data for the third scenario in day with maximum thermal demand.

consumption. The results illustrated how using a battery besides decreasing operational cost, could increase self-consumption and decrease dependability to the grid. Moreover, battery can help energy hub to avoid buying electricity from grid when the price of electricity is high under dynamic pricing.

As the future work, to link energy carriers and decrease the cost more efficiently, it is planned to add a hot water storage to meet the thermal demand for space heating. Furthermore, adding uncertainty to the energy demand and PV production are other issues which should be taken into account.

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