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Flexibility of a combined heat and power system with thermal energy storage for district heating

Thomas Nuytten [a,b,*], Bert Claessens [a,b], Kristof Paredis [b,1], Johan Van Bael [a,b], Daan Six [a,b]

[a] Energyville (joint venture of VITO NV and KU Leuven), Dennenstraat 7, 3600 Genk, Belgium
[b] Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium

HIGHLIGHTS

- ▶ A generic model for flexibility assessment of thermal systems is proposed.
- ▶ The model is applied to a combined heat and power system with thermal energy storage.
- ▶ A centrally located storage offers more flexibility compared to individual units.
- ▶ Increasing the flexibility requires both a more powerful CHP and a larger buffer.

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ABSTRACT

The trend towards an increased importance of distributed (renewable) energy resources characterized by intermittent operation redefines the energy landscape. The stochastic nature of the energy systems on the supply side requires increased flexibility at the demand side. We present a model that determines the theoretical maximum of flexibility of a combined heat and power system coupled to a thermal energy storage solution that can be either centralized or decentralized. Conventional central heating, to meet the heat demand at peak moments, is also available. The implications of both storage concepts are evaluated in a reference district. The amount of flexibility created in the district heating system is determined by the approach of the system through delayed or forced operation mode. It is found that the distinction between the implementation of the thermal energy storage as a central unit or as a collection of local units, has a dramatic effect on the amount of available flexibility.

1. Introduction

The growing importance of distributed (renewable) energy resources in energy grids introduces a mismatch between supply and demand and hence calls for demand-side management (DSM), which requires flexibility at the demand side. Several studies have confirmed that demand-side flexibility is a cost-effective means of enabling increased integration of renewable energy sources [1–3]. Additionally, flexibility in the energy demand allows for intelligent control algorithms steering the coupling between decentralized energy resources and energy storage, leading to economical and practical benefits when applied to modern combined heat and power (CHP) technologies [4–8]. Haeseldonckx et al. [9] calculated that the incorporation of a thermal energy storage (TES) in CHP installations can improve the net reduction in CO_2 emission associated with cogeneration by a factor of three. It was established that the main reasons for these improvements are the higher operating times and increased continuous operation of the cogeneration unit. Fragaki et al. [10] pointed out that the day and night electricity tariff structure in the United Kingdom creates opportunities for TES-based economic balancing. A case study confirmed their general result that a thermal store improves the economics of a CHP plant by up to 15% in terms of yearly weighted average of the electricity tariffs. Streckienė et al. [7] showed that for a district heating network with an annual heat demand of 30 GW h, a simple payback time of 5 years is reachable assuming an appropriate control of the CHP and TES combination using spot market tariffs and employing the CHP-bonuses issued in Germany. Pagliarini and Rainieri [11] analyzed the coupling between TES and cogeneration for an Italian university campus from an economic and energetic point of view. They concluded that while a smaller CHP unit may require more auxiliary boiler heating, in this

* Corresponding author at: Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium. Tel.: +32 14 335820; fax: +32 14 321185.
E-mail address: thomas.nuytten@vito.be (T. Nuytten).
[1] Present address: IMEC Center for Advanced Metrology Solutions, Kapeldreef 75, 3001 Leuven, Belgium. Tel.: +32 16 283438.

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particular case it is preferred over a larger unit assuming a TES of adequate capacity is installed. This may require a large amount of storage volume, and from that point of view, compact TES solutions are currently attracting substantial interest. While the number of commercial applications using thermo-chemical energy storage is still limited, latent heat-based storage using phase change materials (PCMs) offers a number of important advantages over sensible heat-based storage techniques [12–14]. In these materials, the temperature remains constant during the phase transition which allows small working temperature intervals for the thermal systems, while the relatively large energy density may reduce the amount of volume required for storage by a factor of up to three when used in space heating applications [15].

In the present work, an actual heating demand with hourly resolution of a small district serves as the input for a generic model that assesses the flexibility created by the combination of a district CHP unit and sensible thermal storage. The characteristics of both the TES and CHP system are varied, and the model determines the theoretical maximum of flexibility, an important parameter of energy systems in a smart grid environment. The energy storage can be either centralized or decentralized, and conventional central heating is also available in order to meet the heat demand at peak moments. Excess thermal energy can be stored in a buffer, hence decoupling electricity and thermal production [16]. A water reservoir was chosen as the thermal energy storage system because of its market maturity and low cost. Based on the respective position of these two coupled systems, two different implementations of the concept can be identified:

- Central district CHP with centralized thermal energy storage.
- Central district CHP with decentralized thermal energy storage.

While providing insight into the flexibility realized by these combinations, the results will facilitate the dimensioning of the relevant CHP and storage characteristics for a given heat demand profile. This research was conducted within the framework of the Linear project [17], a Flemish collaborative smart grid breakthrough project.

2. Methodology

A data set containing the recorded gas and electricity consumption of 100 residential dwellings in Flanders with hourly resolution [17] was used to obtain the aggregated heat demand for a typical residential district as a function of time (the total annual heat demand of the district amounts to 2355 MW h). No distinction was made between space heating water (SHW) and domestic hot water (DHW). Relevant and realistic starting values for the CHP power (P_{CHP}) and buffer size were determined based on the aggregated heat demand. A reasonable choice [10,9] is set at a power of 300 kW_{th} (250 kW_e) for the non-modulating CHP and a storage unit of 800 kW h, reaching a theoretical maximum of about 65% CHP operation time throughout the year.

2.1. Flexibility

In a first step, a more detailed definition of flexibility is worked out [18,19]. The flexibility of the installation allows for changes in the energy use over time and is a valuable property when the supply of energy has an increasingly intermittent character. Although the model is not limited to these specific devices, the system under consideration consists of a CHP with thermal energy storage. One can think of the CHP with buffer as a system that can freely operate between maximal or minimal remaining buffer capacity, and the flexibility is defined in terms of the space between these two extremities. Starting from the accumulated heat demand we first construct a Minimum Curve [MIN_t] where the CHP system is engaged only when the storage capacity is insufficient to meet the current heat demand. The heat demand is met at all times, but the buffer is kept at minimum charge (see Fig. 1). For a time base Δt this gives:

$$MIN_{t+1} = MIN_t + \mathbb{1}_{MIN}(t)P_{CHP}\Delta t + E_{AUX,t} \tag{1}$$

where $E_{AUX,t}$ is the heat production from the auxiliary heating, if appropriate, and $\mathbb{1}_{MIN}(t)$ is an indicator function describing the operation of the CHP system:

$$\mathbb{1}_{MIN}(t) = \begin{cases} 1 & \text{if } Q_{t+1} - Q_t > E_{buffer,t} \\ 0 & \text{if } Q_{t+1} - Q_t \leqslant E_{buffer,t} \end{cases} \tag{2}$$

with $E_{buffer,t}$ the remaining thermal energy present in the thermal energy storage and Q_t the district heat demand at time t.

The Maximum Curve [MAX_t] on the other hand is calculated to maintain maximum charge of the buffer at all times. This curve represents the working pattern of the CHP with the sum of the accumulated heat demand and buffer size as upper limit. The heat production of the CHP should never be higher than the sum of the heat demand and storage capacity since in that situation useful heat is lost. This gives:

$$MAX_{t+1} = MAX_t + \mathbb{1}_{MAX}(t)P_{CHP}\Delta t + E_{AUX,t} \tag{3}$$

Here, $\mathbb{1}_{MAX}(t)$ is an indicator function describing the operation of the CHP system in the regime of the Maximum Curve:

$$\mathbb{1}_{MAX}(t) = \begin{cases} 1 & \text{if } Q_{t+1} - Q_t \geqslant P_{CHP}\Delta t - E_{free,t} \\ 0 & \text{if } Q_{t+1} - Q_t < P_{CHP}\Delta t - E_{free,t} \end{cases} \tag{4}$$

with $E_{free,t}$ the remaining free capacity of the thermal energy storage at time t before it is full.

The time base for these and the following calculations is, in this particular case, set at 1 h, meaning that all parameters such as heat demand and thermal energy stored are evaluated on a 1-h basis. Because of the discrete time base, both the Minimum and Maximum Curve are discontinuous and the precise behavior of the step-like operating curves will depend on the size of the buffer and power of the CHP. When the CHP is operating, the heat produced is visualized by the Minimum and Maximum Curve as an increase at a rate (slope) which is equal to the CHP power. When the CHP is not operating, the heat demand is met by the energy stored in the buffer, and the operating curves go through a plateau.

Any specific operation sequence of the CHP and buffer system corresponds to a certain path in between the Minimum and Maximum Curve and hence the possible working area for the system has been defined. The construction of this flexibility profile offered by the selected devices allows analysis of a variety of parameters and scenarios. Revenue or cost structures can be implemented as the steering parameters to calculate deployment of the flexibility in terms of a financial optimization [19]. In this particular application, the relative position of the thermal energy storage and CHP unit is investigated.

2.1.1. Delayed operation flexibility

By calculating the Minimum and Maximum Curve, the upper and lower limits for the operation mode of the CHP coupled to a storage tank have been defined. In other words, when the actual operation of the CHP is kept in between the Minimum and Maximum Curve, the system is fulfilling the heat demand of the district, while actively using the thermal energy storage. In that sense the coupling of a CHP to a storage unit creates a certain degree of flexibility, and the use of the CHP can be shifted in time. Indeed the time difference between the Maximum and Minimum Curve (see left panel of Fig. 1) is equal to the time the CHP can be kept idle