European University Institute

ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES

EUI Working Papers

RSCAS 2012/48
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
Loyola de Palacio Programme on Energy Policy

THE ROLE OF THERMAL STORAGE AND NATURAL GAS IN A SMART ENERGY SYSTEM

Jeroen Vandewalle, Nico Keyaerts and William D'haeseleer

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
ROBERT SCHUMAN CENTRE FOR ADVANCED STUDIES
LOYOLA DE PALACIO PROGRAMME ON ENERGY POLICY

The Role of Thermal Storage and Natural Gas in a Smart Energy System

JEROEN VANDEWALLE, NICO KEYAERTS AND WILLIAM D'HAESELEER

EUI Working Paper **RSCAS** 2012/48

ISSN 1028-3625

Printed in Italy, September 2012
European University Institute
Badia Fiesolana
I – 50014 San Domenico di Fiesole (FI)
Italy
www.eui.eu/RSCAS/Publications/
www.eui.eu
cadmus.eui.eu

Robert Schuman Centre for Advanced Studies

The Robert Schuman Centre for Advanced Studies (RSCAS), created in 1992 and directed by Stefano Bartolini since September 2006, aims to develop inter-disciplinary and comparative research and to promote work on the major issues facing the process of integration and European society.

The Centre is home to a large post-doctoral programme and hosts major research programmes and projects, and a range of working groups and *ad hoc* initiatives. The research agenda is organised around a set of core themes and is continuously evolving, reflecting the changing agenda of European integration and the expanding membership of the European Union.

Details of the research of the Centre can be found on:
http://www.eui.eu/RSCAS/Research/

Research publications take the form of Working Papers, Policy Papers, Distinguished Lectures and books. Most of these are also available on the RSCAS website:
http://www.eui.eu/RSCAS/Publications/

The EUI and the RSCAS are not responsible for the opinion expressed by the author(s).

Loyola de Palacio Energy Policy Chair

The Loyola de Palacio Energy Policy Chair was created in October 2008 at the RSCAS in honour of Loyola de Palacio, former Vice President of the European Commission and Commissioner for Energy and Transportation in the Prodi Commission. It promotes research in the area of energy policy. It is funded by contributions from donors. Professor Jean-Michel Glachant is the holder of the Chair.

The Chair focuses on the fields of energy economics, law, regulation, as well as geo-politics. It addresses topics such as the *achievement of the EU internal energy market; sustainable energy systems and the environment; energy security of supply; the EU model of energy regulation; the EU energy competition policy; the EU policy towards carbon free energy systems in 2050.*

The series of working papers aims at disseminating the work of academics on the above-mentioned energy policy issues.

For further information
Loyola de Palacio Energy Policy Chair
Nicole Ahner (scientific coordinator)
Email contact: Nicole.Ahner@eui.eu
Robert Schuman Centre for Advanced Studies
European University Institute
Via delle Fontanelle, 19
I-50016 San Domenico di Fiesole (FI)
Fax: +39055 4685755
http://www.loyola-de-palacio-chair.eu

Abstract

Smart grids are considered important building blocks of a future energy system that facilitates integration of massive distributed energy resources like gas-fired cogeneration (CHP). The latter produces thermal and electric power together and as such reinforces the interaction between the gas and electricity-distribution systems. Thermal storage makes up the key-source of flexibility that allows decoupling the electricity production from the heat demand. However, smart grids focus on electricity, often disregarding the role of gas and thermal storage in overall smart energy systems. We find that the technical impact of a massive introduction of CHP on the gas-distribution network is limited in most cases, even providing opportunities to free up capacity. Taking the consumer's viewpoint, we highlight the economic importance of the thermal storage tank, which requires a thermal capacity of two to three times the hourly thermal power output of the CHP to optimize electric power production and limit thermal losses. Further increasing the storage tank size can increase the gas-distribution capacity that can be marketed by the distribution system operator, but practical constraints in terms of dedicated land area have to be considered as well.

Keywords

Smart Grids, Cogeneration, Natural Gas, Energy Storage

Nomenclature

C	thermal capacity storage tank	kWh
c_p	thermal capacity of water	J/kg.K
$\dot{E}$	electric power CHP unit	kW
$\dot{g}$	gas demand	kWh/h
$\dot{g}_{max}$	maximum in reference gas demand	kWh/h
$\dot{h}$	heat demand	kWh/h
L	loss factor	kWh/h
m	hourly average boiler modulation	-
p_e	electricity price	€/kWh
p_g	gas price	€/kWh
$\dot{Q}_c$	thermal (dis)charging power	kWh/h
$\dot{Q}_{cB}$	thermal power condensing boiler	kW
$\dot{Q}_{CHP}$	thermal power CHP	kW
R	ratio thermal to electric power CHP	-
s	CHP on/off variable	-
t	time	h
T	temperature	K
V	volume of the storage tank	m^3
x	storage tank energy contents	kWh
x_{Min}	minimum energy level storage tank	kWh
x_{Max}	maximum energy level storage tank	kWh

Greek symbols

α_E	electric efficiency CHP unit
α_Q	thermal efficiency CHP unit
η_{cB}	thermal efficiency condensing boiler
η_{st}	thermal efficiency storage tank
ξ	peak increase gas demand
ζ	gas demand peak increase

Subscripts

t	time step

I. Introduction[*]

Smart grids are considered as an important next step towards a reliable and sustainable energy provision [1, 2]. The definition of a 'smart grid' by the European Smart Grid platform [3] refers to a reliable electricity provision with integration of distributed energy resources (DER) and active participation of consumers. Ample research is being done on how distributed energy resources (DER) like solar and wind energy, and cogeneration (CHP [1]) can be used in an optimal way for different stakeholders. Most research focuses on the electricity grid, see e.g. [3], even though the gas grid plays an important role for network balancing when renewable energy sources are deployed on a large scale, e.g. through cogeneration [4]. The latter is a technology that produces electric power and thermal power simultaneously and as such is particularly interesting on the distribution system level. Because CHPs are often gas-fired, the gas distribution and electricity distribution systems become interacting systems. Heat pumps make up another example of a technology linking heat, electricity and gas as they draw electricity from the grid to produce heat and partially replace conventional gas-fired boilers. These applications will influence the natural gas demand and the natural gas distribution grid. Furthermore, thermal energy can be stored much easier than electric energy, providing much needed flexibility to the electricity and gas distribution systems. This role of thermal storage in a smart grid context and its impact on the gas system has to be accounted for as well. Therefore, *smart energy systems* is preferred as a concept over smart grids to point at the role of the gas system and thermal storage beyond the pure electricity smart grid.

CHP is a very interesting technology because of its efficient fuel utilization and the possibility to interact with the electricity grid. Moreover, contrary to most renewable DER, CHP is a dispatchable source of electric power because of the continuous availability of gas as its fuel. Yet, without thermal storage CHP would be entirely heat driven as there are more efficient ways of producing electricity if the heat has no value. With thermal storage, the heat production can be decoupled from the heat demand, giving flexibility to produce electricity based on incentives from the electricity system. Next to offering flexibility, thermal storage also leads to more energy savings, less CO_2 production and an increased lifetime of the CHP unit [5]. The dependency on a reliable fuel and its dispatchability make cogeneration on a small scale (micro- or mini-CHP units) suitable for small users like households, an interesting part of a smart grid as it contributes to the reliability of the electricity system and it allows consumers to become active players if they have thermal storage.

However, the reliability of the gas distribution system is affected by changing gas demand through the addition of gas-fired CHPs to a gas network that has a limited capacity to provide gas to a specific location. Therefore, it is useful to examine the impact of CHP on the gas distribution grid. In general, the average gas demand is expected to increase with a rising penetration level of CHP, potentially leading to physically congested pipelines. However, the impact depends on the exact gas demand of the CHPs, and these depend on the use of thermal storage and the interaction between the gas and electricity distribution systems.

Besides studying the technical impact on the gas distribution network, the economic rationale of the customer to use CHP should be investigated as that analysis sheds light on how the gas demand can look like if the role of thermal storage is taken into account. Thermal storage in the framework of

---

[*] This work was partly funded by the research project on 'local intelligent networks and energy active regions' (LINEAR) supported by the Flemish agency for innovation through science and technology (IWT).

The authors would like to thank Ms. J. Zapata of the University of Leuven (KU Leuven) Energy Institute - branch Applied Mechanics and Energy Conversion.

[1] Cogeneration and combined-heat-and-power (CHP) are synonyms.

smart grids has been looked at before by [6], the optimization of CHP with thermal storage has been modelled by [7] and [8] shows the importance of thermal storage to reduce carbon emissions.

The aim of this paper is to focus on the gas distribution system and investigate how the smart grid with massive CHP penetration and thermal storage affects it, or better, how these elements of a smart energy system interact. To this end, we examine the technical impact on the gas system and analyze the economic impact on the consumer who is driven by a demand for thermal and electric energy services.

To determine the effects mentioned above, we use a simplified model of a gas distribution system that is discussed in section II together with a method to size the CHP unit and the accompanying thermal storage tank. The technical impact of massive introduction of CHP will be examined in section III followed by an economic analysis regarding CHP from a user's point of view in section IV. Section V presents a number of methods to increase the capacity of the gas network with thermal storage in the presence of CHP. Ideas for further work are given in section VI and finally, section VII summarizes the main conclusions from this work.

II. Models and Equations

This part describes the models and equations used in this work. First the main assumptions are given. This is followed by a discussion of the heating system simulation model.

A. Assumptions

The heating systems of a number of households will be simulated to see what their resulting gas demand is. To find the gas demand of a household, the heating system, including the CHP unit, is simulated, such that if fulfills an imposed heat demand. To be a realistic representation of the situation in Flanders [2], this heat demand is on its turn derived from measured gas demand, where we assume that neither CHP units, nor thermal storage tanks nor domestic hot water production were present, such that the heat demand and the measured gas demand have a proportional relation. These measured gas demands will act as reference gas demands, to compare the simulated gas demands with to see the influence of CHP and thermal storage, as schematically depicted in Fig. 1.

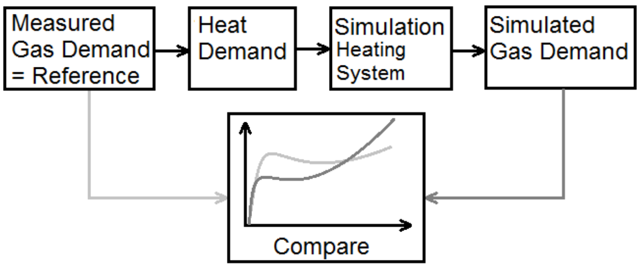

Fig. 1. Schematic representation of the work flow. The heat demand is derived from the measured gas demand, which acts as a reference. The heat demand has to be covered by the heating system in a simulation model. The output is the simulated gas demand; this can be compared to the reference gas demand.

The natural gas distribution network is represented by a hypothetical model, disregarding the pressure losses and the location of the consumers in the network. The capacity of the network is expressed in

[2] Flanders is the northern part of Belgium, with six million inhabitants of which most households have a natural gas connection. The reference gas demand profiles that are used have a representative distribution for the Flemish scenario, regarding the number of inhabitants, the type of house and the annual gas demand.

terms of power (kWh/h [3]). Assuming that the gas network is congested when the reference gas demands are applied to it, the capacity of the network is the highest gas demand that occurs when all connected households' reference gas demands are added together.

The heat $\dot{Q}_{CHP}$ to electric output $\dot{E}$ ratio R of the CHP is assumed to be 4:1 and the fuel utilization ratio amounts to 95%. The fuel utilization ratio is the ratio of the useful energy—both electric and thermal—to the primary energy. Equivalently, this is the sum of the electric efficiency α_E and the thermal efficiency α_Q of the CHP. In this work, $\alpha_E = 19\%$ and $\alpha_Q = 76\%$. The condensing boiler efficiency η_{cB} is assumed 100% for simplicity. It is also assumed that the CHP unit does not modulate.

The price for electricity sold to the electricity network is assumed the same as the price to buy it, amounting to 0.15 €/kWh by night and 0.22 €/kWh by day. Furthermore, the electrical system will be regarded as exogenous and all produced electricity by the CHP is always sold to the grid. The gas price is assumed 0.06 €/kWh unless mentioned differently.

We suppose a perfectly stratified thermal storage tank. This means that the hot water does not mix with the cold water in the tank, and that the thermal conductance of the water is zero. From an energy point of view, the perfectly stratified model gives good results compared to the actual stratified model, which is more complex but describes the physics of heat storage more accurately [9].

B. The Heating System Simulation Model

The heating system that will be modelled consists of a CHP unit with a separate auxiliary boiler and a thermal storage tank, see Fig. 2. The heat demand is always imposed. The decision of the operation of the boiler, the CHP and the storage tank is left to an optimization of the model and the gas demand is the output.

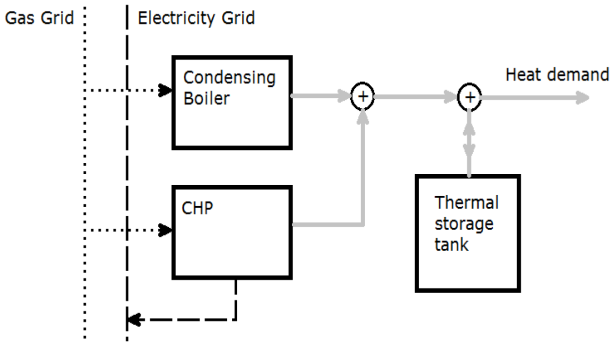

Fig. 2. The model layout of the CHP system with auxiliary boiler and a thermal storage tank.

The gas consumer minimizes the costs for using the auxiliary boiler, the CHP and the storage tank. This means that the solver will determine when the CHP or the auxiliary boiler are on, and when the thermal storage tank is (dis)charged such that the annual cost of the gas minus the electricity revenues—for every customer in the network separately—are minimized. This objective function is expressed in Eq. (1) where z (€) is the adapted [4] annual gas cost, $\dot{g}_t$ (kWh/h) is the hourly gas demand of both the boiler and the CHP, p_g (€/kWh) is the gas price per unit of energy, s_t is zero if the CHP is

[3] Power is normally expressed as *kW*. However, for some quantities like the heat of the gas demand, we prefer to use *kWh/h* to express that it concerns the hourly average power, as the time step for the simulations is one hour.

[4] The term *adapted annual gas cost* is used here because the revenues from the produced electricity are subtracted from the annual gas bill.

off during hour t or one elsewhere[5], $\dot{E}$ (kW) is the electric power of the CHP and $p_{e,t}$ (€/kWh) is the price per unit of electric energy during hour t. The time step Δt is one hour.

$$z = \sum_{t=1}^{8760} p_g \dot{g}_t \Delta t - \sum_{t=1}^{8760} p_{e,t} s_t \dot{E} \Delta t \tag{1}$$

Next to the cost function, there are several energy-balance equations that describe the heating system. Equation (2) describes the heat balance: for every hour t, the heat demand $\dot{h}_t$ (kWh/h) must be met either by the boiler, the CHP or the storage tank. The maximum thermal power of the boiler is a parameter $\dot{Q}_{cB}$ (kW) and the variable m_t is the hourly average modulation of the condensing boiler. The thermal power of the CHP is $\dot{Q}_{CHP}$ (kW). The (dis)charging power of the storage tank during hour t is the variable $\dot{Q}_{c,t}$ (kWh/h).

$$\dot{h}_t = m_t \dot{Q}_{cB} + s_t \dot{Q}_{CHP} - \dot{Q}_{c,t} \tag{2}$$

Equation (3) expresses the gas balance, i.e. the gas demand $\dot{g}_t$ (kWh/h) is the sum of the gas demand of the condensing boiler and the gas demand of the CHP. The thermal efficiency of the boiler is η_{cB} and the thermal efficiency of the CHP is α_Q .

$$\dot{g}_t = m_t \frac{\dot{Q}_{cB}}{\eta_{cB}} + s_t \frac{\dot{Q}_{CHP}}{\alpha_Q} \tag{3}$$

Equation (4) expresses the temporal energy balance in the thermal storage tank and can be found by rearranging the conservation of energy equation applied to a perfectly stratified storage tank. The thermal energy contents of the tank at hour t is x_t (kWh) and η_{st} (<1) represents the thermal losses due to the high temperature water portion in the tank. The losses due to the temperature difference between the low temperature tank and the surrounding air temperature are denoted by L (kWh/h). The (dis)charging energy at hour t is $\dot{Q}_{c,t}\Delta t$ and the (dis)charging efficiency is assumed to be 100% here.

$$x_{t+1} = \eta_{st} x_t + \dot{Q}_{c,t} \Delta t - L \tag{4}$$

The constraints are: the storage tank starting energy equals the minimal operating energy (Eq. 5), the (dis)charging power is limited to 50 kW (Eq. 6), the hourly average modulation of the boiler m_t must be in the interval [0,1] (Eq. 7) and the stored energy inside the storage tank must always be more than the minimal and less than the maximal operational capacity (Eq. 8).

$$x(1) = x_{Min} \tag{5}$$

$$-50 \leq \dot{Q}_c \leq 50 \tag{6}$$

$$0 \leq m_t \leq 1 \tag{7}$$

$$x_{Min} \leq x_t \leq x_{Max} \tag{8}$$

C. Sizing of the CHP and the storage tank

The CHP cannot be designed to meet the maximum heat demand because it would be switched on and off very frequently, leading to transient behavior that may shorten the lifetime and the possible energy savings [5]. Therefore, the CHP unit can be accompanied by an auxiliary boiler and a thermal storage

---

5 The reason to choose for a binary representation of the CHP status is two-fold: first, most CHP units are not capable of modulation, or at least not much; second, this binary formulation is equivalent with a minimum up-time of one hour.

tank. Using the 'biggest rectangle method' [10] to size the CHP unit allows it to run more continuously, resulting in more energy savings and CO_2 reductions.

The method places heat demands of a household in descending order in a load-duration diagram, as depicted in Fig. 3. Next, the rectangle with the largest area that can be subscribed by the load-duration diagram is determined. The intersection of the rectangle with the vertical axis represents the optimal value for the thermal power of the CHP. Assigning a thermal power of the CHP unit according to this method leads to a maximum annual thermal, and consequently electric, energy production with the CHP.

It has to be noticed that this method does not regard thermal storage, and that taking this in to account would lead to different sizes of the CHP unit. For simplicity however, all units in this paper will be sized according to this biggest rectangle method.

In this paper, the size of the thermal storage tank is expressed relative to the thermal energy that the CHP produces in one hour. The storage tank volume, which is directly proportional with its thermal capacity, will be denoted as Relative Storage Capacity (RSC). The thermal capacity C (kWh) and the volume V (m^3) of the tank have the following relation:

$$C = V\rho c_p \Delta T / 3600000 \tag{9}$$

where $\rho = 1000\ \frac{kg}{m^3}$ is the density of water, $c_p = 4180\ \frac{J}{kg.K}$ is the thermal capacity of water and $\Delta T = 40\ K$ is the temperature difference between the high and the low temperature part of the storage tank. 3600000 is the conversion factor from J to kWh, which will be more convenient here. The Relative Storage Capacity can be calculated as:

$$RSC = \frac{C}{\dot{Q}_{CHP}\Delta t} \tag{10}$$

where $\dot{Q}_{CHP}$ is the thermal output of the CHP and Δt is the time step of one hour. As will be explained in section IV, an economically good thermal storage capacity is two to three times the thermal output produced in one hour by the CHP. In this paper, a reference value of 2.3 will be taken as the the storage size.

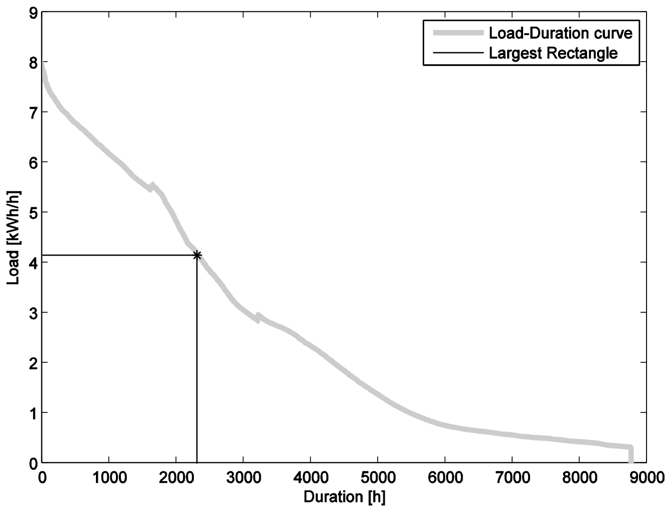

Fig. 3. An example of CHP sizing with the largest rectangle under the load-duration curve. According to this method, the CHP in this example should have a thermal output of 4.15 kW and will be on for 2260 hours per year.

A CHP that is sized with this method will most likely be on during a cold winter day—also at night—regardless of the electricity price, as long as that price is positive. In winter, the CHP would cover a base load of electricity. During spring, autumn and especially the summer, the CHP is much more responsive to the electricity price levels because it will not be on all day. As this paper focuses on the high demand during winter days, the impact of dynamic electricity pricing is disregarded here.

III. Technical Impact on the Gas Grid

This section examines the technical impact of cogeneration on the gas distribution network. In other words, we investigate whether the gas network is able to cope with a massive introduction of CHP. The most important parameter to check this is the total gas demand of all households connected to the grid, which should not be higher than the capacity of the gas network in order to be able to supply the households. First, a theoretical maximum impact is derived, followed be a more practical maximum peak demand. The scenarios in this part assume a massive introduction of CHP. Hence, all users are equipped with CHP and thermal storage.

A. Theoretical maximum peak demand

The theoretical 'worst case' scenario is when all customers act exactly the same; there is no averaging effect and all gas demand peaks will therefore occur at the same time. Since all customers act the same, it is sufficient to study the effect of only one customer. It is examined what happens if a CHP is fitted with thermal storage to fulfill an average heat demand. Applying the largest rectangle method for sizing, we find a CHP with a thermal power $\dot{Q}_{CHP}$ of 4 kW and a reference buffer size (RSC = 2.3) of approximately 200 L. We assign an electric output $\dot{E}$ of 1 kW, so the heat to electricity output ratio R of the CHP is 4:1.

Next, we derive what the maximum increase in peak demand would be in the absence of storage. The maximum peak demand will occur on the coldest day of the year. During the peak heat demand, the CHP will definitely be on because its thermal output is always smaller than the highest heat demand; see Fig. 3. So, a part of the heat demand $\dot{Q}_{CHP}$ will be covered by the CHP and the remaining part by the auxiliary boiler. The gas demand required to produce a thermal power of $\dot{Q}_{CHP}$ with the CHP is $\dot{Q}_{CHP}/\alpha_Q$ while the required gas demand to produce this heat with the condensing boiler is $\dot{Q}_{CHP}/\eta_{cB}$. Recalling that the boiler efficiency was assumed 100%, the extra gas demand that is required to produce a thermal power of $\dot{Q}_{CHP}$ with the CHP unit instead of the condensing boiler can be written as:

$$\dot{g}_{extra} = \frac{\dot{Q}_{CHP}}{\alpha_Q} - \frac{\dot{Q}_{CHP}}{\eta_{cB}} \tag{11.a}$$

$$= \dot{Q}_{CHP}\left(\frac{1}{\alpha_Q} - 1\right) \tag{11.b}$$

which equals 1.26 kW. This leads to a gas demand peak increase ζ of 14%, see Eq. 12 where $\dot{g}_{max}$ is the highest gas demand of the reference gas profile.

$$\zeta = \frac{\dot{g}_{max} + \dot{g}_{extra}}{\dot{g}_{max}} \tag{12}$$

This value will be taken as a limit value for the increase of the peak gas demand due to the use of CHP compared to boiler-only heating.

Now we examine what the influence of thermal storage is on this theoretical limit. Simulations with different buffer sizes show an increase ζ of about 14%—confirming the predicted 14%—regardless of the storage size, see Fig. 4. This figure shows the gas demand for a typical winter day and the gas demands that result when a CHP is present with different thermal storage sizes. The buffer sizes are:

(i) no storage, (ii) 100 L, (iii) 400 L and (iv) 750 L. Regarding the impact of the storage tank size on the peak gas demand, not much effect can be observed. Larger tanks delay the occurrence of the peak gas demand in time. This is because they store thermal energy at night to prolong the CHP runtime and release it by day. This case is economically optimized for the customer, so, increasing the buffer size beyond a value that allows the CHP to be on 24 hours a day will not have any influence anymore on the peak gas demand. Increasing the buffer size beyond the optimal value is also be sub-optimal for the customer due to the extra thermal losses of the tank. It can also be noted in Fig. 4. that the line for 100 L shows a fallback of gas demand by night because the buffer is not large enough to store enough heat from the CHP to keep it on all night.

The 'theoretical limit' for the peak gas demand increase ζ_{limit} = 14% can be regarded as being independent of the buffer size and the electricity price. Recall that this is for CHP units with a heat to electric output ratio of 4:1, a fuel utilization ratio of 95% and an average user.

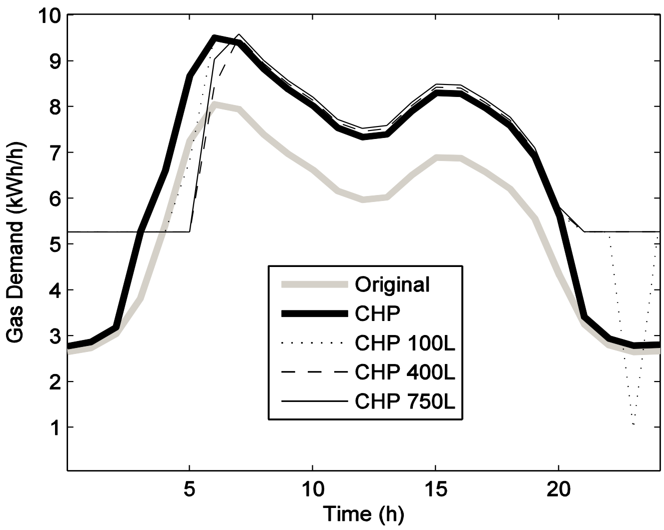

Fig. 4. The gas demand for a household with an average heat demand. The grey line is the original, reference gas demand without CHP on a typical cold day. The thick black line is the gas demand for this household with CHP without storage. The gas demand when a 100 L of thermal storage is present shows a fallback at night, because the tank is not big enough to store enough heat from the CHP to keep it on all night. The lines for higher storage sizes show that the CHP can be on all night. The influence of the storage size on the peak gas demand is negligible.

B. Practical maximum peak demand

In reality, however, there are numerous users and the effects of CHP on the gas network will be averaged out. To find a more realistic peak demand, a variety of consumers are now being simulated with different heat demand profiles. In the simulation, every household is fitted with a CHP and a thermal storage tank with the reference size.

The results show a peak gas demand increase ζ of about 1% on average for all users, compared to no CHP usage, which is much smaller than the predicted theoretical limit of 14%. An example of how the average gas demand of a household looks on a typical winter day can be seen in Fig. 5 for different sizes of the storage tank. We note that this result is obtained as an average over all users. Some users provoke local peak gas demand increases that range from -32 to +8%, which is still smaller than the theoretical limit, but nevertheless this could lead to local problems in the gas distribution network.

In Fig. 6, we show how the peak increase ζ changes with the RSC. This is expressed relative to the highest peak demand in the reference gas demand $\dot{g}_{max}$. The actual peak increase is case dependent—that is why Fig. 6 is not a smooth curve—but in general, it decreases with increasing relative storage capacity, even when an RSC of 2.3 is exceeded, up to an RSC of 7. The latter observation is in contrast with the findings from part A of this section, where increasing the storage tank size beyond the reference value did not have much influence. This outcome occurs because the actual profiles can differ very much from the average profile, such as the one depicted in Fig. 4. For some heat demand profiles, a RSC of 2.3 is not sufficient to keep the CHP running all night; a higher RSC value would therefore be needed. In the case that was simulated here, the average on-time for the CHP units was 76% during the day depicted in Fig. 5. That is why further increasing the storage beyond 2.3 still has an effect in this analysis. However, determining the ideal value for every individual profile is beyond the needs of this analysis. The main observation here is that a massive introduction of CHP does not lead to a peak increase for RSC values of 2.3 and higher, but to a peak demand decrease.

We point out that all CHP sizes have been considered here; whereas in practice, there are only a number of commercially available sizes. The thermal size in this paper has been set to whatever the outcome of the maximum rectangle method was.

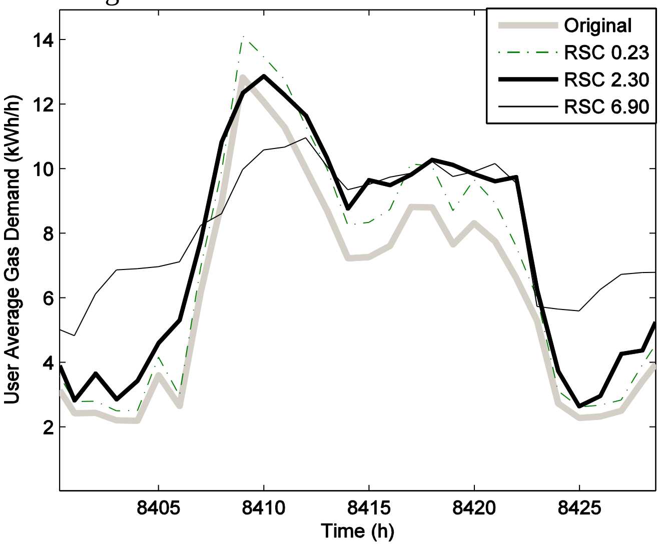

Fig. 5. The average gas demand per consumer on a cold winter day for different sizes (RSC) of the thermal storage tank. The grey line represents the average reference gas demand. Further increasing the RSC beyond 2.3 has a flattening effect on the gas demand. This is because an RSC of 2.3 is not optimal for every consumer.

C. Conclusions on the technical impact on the gas network

It can be concluded that, for our cases and assumptions considered, a massive introduction of CHP would not lead to general technical problems, as long as the thermal storage tanks have a capacity of two or more times the hourly thermal output of the CHP. However, local problems in congested pipelines could occur, especially in neighborhoods with similar users. We consider a peak demand increase of 14% as a limit, i.e. when all users act exactly the same, which is not likely to occur. Increasing the storage size beyond an RSC of 2.3 further decreases the gas demand peak, creating the opportunity to free up capacity in the gas distribution network.

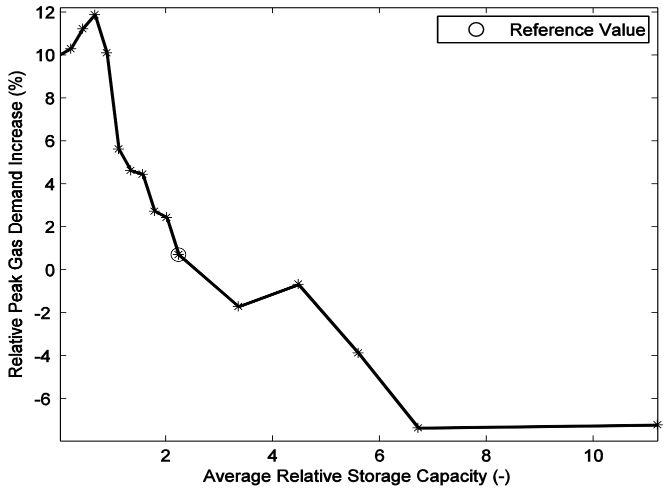

Fig. 6. The peak gas demand increase caused by CHP relative to the original peak demand as a function of the relative storage capacity, averaged per user. The actual peak increase depends on the case, but generally decreases with the relative storage capacity. From an RSC of 7 on, the impact on the peak demand is negligible.

IV. Economic Analysis

This part analyzes the economic situation of a customer with a CHP unit compared to without CHP. We will examine the impact of the storage tank size on the annual gas cost.

A. Impact of the storage tank size

It will be examined how the annual gas cost—minus the electricity revenues—varies as a function of the buffer size. This cost is referred to as *adapted cost*. A number of simulations are performed with different buffer sizes. The heat demand profiles are the same as in section III. To simplify this analysis, we look at the average result of all users.

The results are shown Fig. 7, in which the average adapted gas cost per customer is depicted. This cost is put relative to the cost without CHP. The relative cost amounts to about 73% when no thermal storage is available, meaning that the introduction of the CHP reduces costs by 27% thanks to the electricity revenues. The relative gas cost drops quickly to 55% or below when the RSC is increased to 2 or 3. This shows the importance of well-sized storage tanks. Further increasing the RSC beyond 3 makes only a small difference and for RSCs over 5 the relative cost starts to rise again. This is due to the fact that bigger storage tanks have more thermal losses for the same amount of stored energy.

Fig. 7 also depicts the relative costs when a variable investment cost for the storage tank is taken into account (grey dashed line). From a survey of publicly available commercial information, we derived the following cost function for a storage tank: 900 € + 600 €/m^3. It is also assumed that the storage tank lifetime is 15 years and that the interest on the storage tank investment is 5%. The cost of the surface occupied by the tank is not taken into account. It is assumed that the customer was going to invest in a CHP anyway, so this investment will not be taken into account. The grey curve shows that it is interesting to have a tank with an RSC of about 3 to 4. Taking into account that customers usually prefer smaller tanks, or they don't have much space, an RSC of 2 to 3 can be considered as ideal. For higher RSCs, relative costs start rising again, making these storage sizes economically and practically not interesting for the customer. These numbers support our decision to use a reference RSC value of 2.3 earlier in this paper.

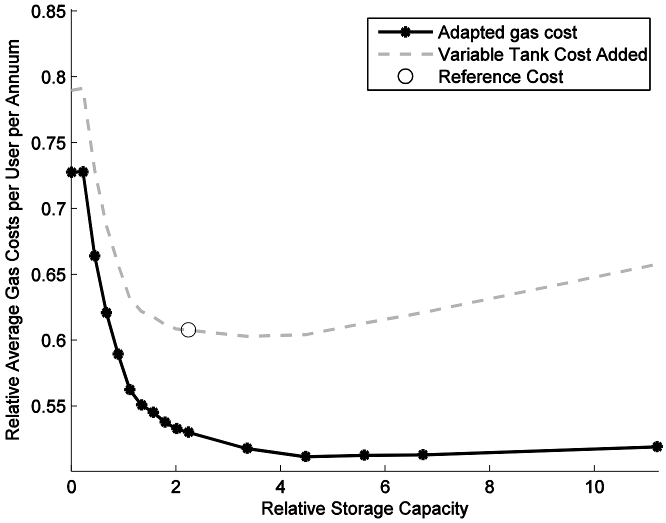

Fig. 7. Average adapted annual gas cost relative to average annual gas cost without a CHP, as a function of the RSC. For RSCs of 2 to 4, the cost reduction becomes low and from a RSC of 4 to 5, the costs start to increase again due to the thermal losses of the tank. When the storage tank costs are included, the optimal RSC further decreases.

B. Conclusions on the economic analysis

Thermal storage is economically very interesting to increase the electricity revenues from CHP. Analysis shows that the economic optimal RSC is 3 to 4. Considering that users favor smaller tanks, a RSC of 2 to 3 is regarded as a reference value. The reference buffer size reduces relative costs by about 25 percentage points compared to the no storage case, and by about 50% compared to the benchmark case without storage and without CHP.

V. Analysis of the System

We have looked at the technical impact on the gas system and analyzed the economics that drive the customer, and in this part we bring these two aspects together in an analysis of the system. In this paper, *system* means the whole of all users that are going to be equipped with CHP and the gas distribution network with its operator (DSO). It has been shown in previous sections that storage is crucial to make an interesting economic situation for the user. Technically, the probability of supply problems is small. However, local problems could occur, especially in congested pipelines. Thermal storage could help to spread the load without the need to physically intervene in the gas network. Furthermore, thermal storage could also be used to flatten the gas demand in such a way that capacity is cleared in the gas network, e.g., extra users could be added to the same pipeline. First, we calculate how much capacity could theoretically be freed up with storage. Then, the influence of the storage size is studied, followed by an examination of how the gas demand can be shifted without affecting the CHP operation.

A. Maximum capacity gain

First, we analyze how much extra capacity could be made available in the gas network by having thermal storage present. Suppose a congested network when the reference gas demands are applied to it, i.e. before the introduction of CHP and storage. By consequence, the peak gas demand in the benchmark case equals the maximum capacity (667 kW) of the gas distribution network. To create extra capacity, the gas demand could be flattened out with the aid of thermal storage. Theoretically, a completely flat gas demand over the entire year could be achieved, implying a required capacity of

138 kW. This is practically unfeasible, though, because very large storage tanks would be needed, also creating huge thermal losses.

To find a more realistic flattening value, thermal storage will only be considered over a maximum of 24 hours. The day with the highest daily mean gas demand in the network will be determining then for how much the gas demand can be flattened. This design rule leads to a minimal required capacity of 394 kW in our example. Comparing this minimum to the actual capacity, only 394/667 = 59% of the actual capacity would be sufficient to supply gas to all households in the reference scenario, assuming lossless thermal storage. This would free up 41% of the capacity that could be addressed for new households by the DSO.

However, it should be analyzed if all these households are fitted with a CHP, whether it is still possible the feed all CHP units simultaneously with only 59% of the capacity. The required gas demand to feed all the units connected to this network at the same time is 417 kW, and this leads to a ratio of 417/667 = 63% compared to the actual capacity, which could theoretically still lead to 37% of free capacity. It has to be noticed that this value does not account for the extra gas demand due to thermal losses in the storage tank. Whether this capacity clearing can be obtained will be analyzed now in the following sub-sections.

B. Increasing the buffer size

From section IV, we know that increasing the storage size beyond the reasonable size from a customer point of view is generally not economically interesting. However, further increasing the buffer size seems to decrease the peak gas demand, as demonstrated in the second part of section III.

The peak gas demand increase is depicted in Fig. 6 where it can be observed that increasing the RSC beyond a value of 7 has no further capacity-clearing impact on the gas network. This is the size that allows the CHP to be on uninterruptedly in a cold period, and the gas demand is little affected with further increasing of the storage size. For a RSC of 7, we observe that the peak gas demand is about 7% lower than the original one, which leads to only a fraction of the 37% potentially clearable capacity mentioned in the previous part of this section.

However, this 7% can lead to interesting opportunities for the DSO. The DSO might consider paying a compensation to CHP owners as an incentive to install a bigger tank than would be optimal from the customers point of view. We analyze what costs are involved for the customer to install a storage tank with an RSC of 7 instead of 2.3: the relative adapted gas cost including storage costs approximates 62.3% for an RSC of 7 (Fig. 7), which is only 1.6% more than for a RSC of 2.3. This observation suggests there is a big reward for the DSO compared to the small extra cost for larger storage tanks. However, this is disregarding other costs for the customer like occupied space for the storage tank. Other practical constraints might also limit the true potential of big storage tanks.

C. Boiler shift

We found that increasing the storage tank size flattens out the gas demand, until a value (RSC = 7) that allows the CHP to be on continuously. Further increasing the RSC has a negligible impact on the peak gas demand. Another way to lower the peak gas demand is to shift the gas demand from the auxiliary boiler. We analyze how we can shift this boiler demand without changing the CHP operation (for an RSC of 2.3). To this end, the maximum gas demand of the auxiliary boiler is restricted to a certain value; consequently the boiler has to produce heat to be stored during an off-peak period. The storage tank can then assist the boiler during the peak period. Therefore, extra thermal storage volume is needed, next to the reference RSC value of 2.3. We illustrate this flattening process in Fig. 8 where the thick black line represents a normal gas demand during a cold day in the presence of a CHP and reference sized storage tank. The rectangle below represents the gas demand due to the CHP that is assumed constantly on that day. In the example shown in Fig. 8, the gas demand of the boiler will be flattened to an arbitrary chosen level. This has the consequence that the extra heat during the peak period has to be provided by the storage tank, and that the tank has to be loaded off-peak.

The same method of the example is applied now to the heat demand profiles used in this paper. For every user profile, the restriction on the maximum gas demand is calculated, e.g. the highest daily mean gas demand. Adding all these separate maximum levels together, we obtain that the gas demand in the network could be limited to 584 kW, leading to a maximum capacity clearing of 584/667 = 12%. The potential for capacity clearing (12%) is rather small compared to the maximum prediction (37%) because it is based on the highest daily mean gas demands per user, which do not necessarily occur on the same day. To reach a higher possible capacity increase, the restriction that sets the maximum gas demand per user should have be dynamic and change e.g. every day. This is would go too far in this work and therefore, this will not be analyzed.

The results (Fig. 9) show a slightly smaller peak demand decrease (11%) than predicted (12%). This is because the prediction does not take the extra gas demand into account that is caused by the extra thermal losses for storing the heat. The cost analysis shows that for a RSC of 10.7, or a capacity clearing of 11%, the costs rise by 4.8%, compared to no boiler shift and a reference tank size. This extra cost is due to the increased thermal losses and due to the costs of the larger storage tank.

It should be noted that in many cases, an RSC of 10.7 is not always practically feasible, and that the difficulty to practical realization lies in an appropriate determination of the restriction on the gas demand per household, without affecting the thermal comfort.

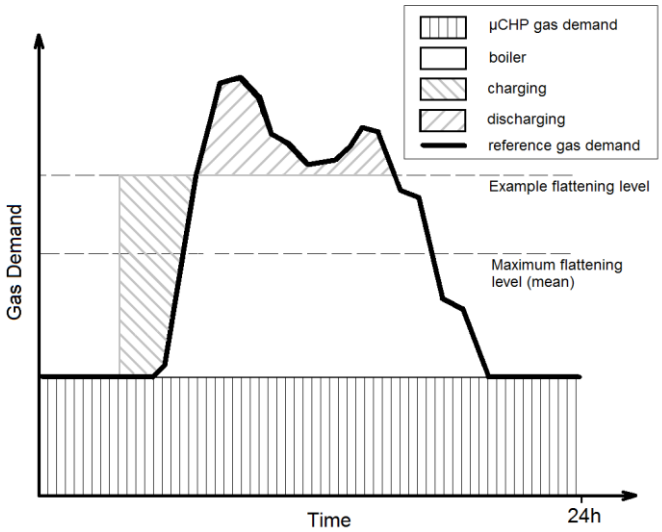

Fig. 8. Example of gas demand flattening by shifting the boiler demand to an off-peak period.

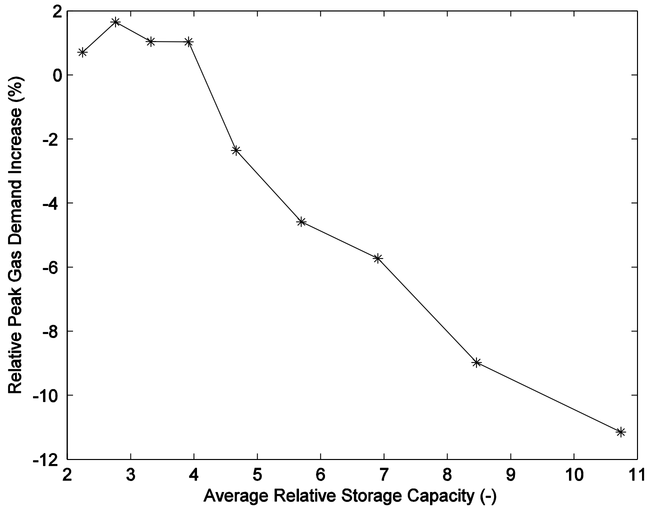

Fig. 9. The relative peak demand increase as a function of the Relative Storage Capacity (RSC) in the case of shifting the boiler time of use. For high RSC numbers, there is a decrease in peak demand, up to 11%. Subsequently, this creates an 11% more capacity in the gas grid.

D. Conclusions on the analysis of the system

Theoretically, the gas peak demand could be lowered by 37%, freeing up 37% of capacity in the grid. Simulations for high RSC values show a decrease in gas peak demand of 7% without special measures. On average, this has a relative adapted gas cost that is 1.6% higher than the reference value. Shifting the boilers gas demand, while keeping the CHP operation with reference storage, frees up an 11% of capacity in the network, for an extra relative cost of 4.8%.

VI. Further Work

Future work will include the analysis of how to determine the local effects in the gas distribution network. One should also put attention to the heat demand profiles separately, next to using methods for averaged users for CHP and storage tank sizing. An optimization per user profile should be done to determine the optimal sizes.

VII. Overall Conclusions

Smart grids are considered as an important next step towards a more reliable and sustainable energy system that will facilitate the integration of distributed energy resources such as wind, solar and cogeneration. The latter can be gas-driven and can be used to react to the electricity market, reinforcing the interaction between the gas and the electricity grid. Therefore, sufficient thermal storage is required to create flexibility so that the heat production can be decoupled from the electricity production. In this light, *smart energy systems* is preferred as a concept over smart grids to point at the role of the gas system and thermal storage beyond the pure electricity smart grid.

We determined the technical impact of a massive introduction of CHP on the gas distribution network in two ways: the worst case shows a maximum gas peak demand increase of 14%; the case with a realistic distribution of heat demand profiles shows an increase of only 1%. It can be concluded that the general impact is limited in most cases, but that local technical problems may occur with high penetration levels of CHP.

Taking the consumer’s viewpoint, we highlight the economic importance of the thermal storage tank, which requires a thermal capacity of two to three times the hourly thermal power output of the

CHP to optimize electric power production and limit thermal losses. Thermal storage is economically very interesting to increase the electricity revenues from CHP. The reference buffer size reduces relative costs by about 25% compared to the no storage case, and by about 50% compared to the benchmark case without storage and without CHP.

We have discussed two ways to increase the capacity of the gas network: the first was to further increase the storage tank size beyond the reference. This follows from the fact that a reference size is not always big enough for every user to keep his CHP unit continuously on during cold days. This has lead to a capacity increase of 7%. The second way was to shift the boiler gas demand and had a capacity increasing effect of 11%. This extra gas distribution capacity that can be marketed by the distribution system operator, but practical constraints in terms of dedicated land area have to be considered as well.

References

[1] Roadmap 2050 [Online]. Available: http://www.roadmap2050.eu/

[2] I. J. Pérez-Arriaga, "Regulatory instruments for deployment of clean energy technologies", EUI Working Paper, European University Institute, Florence, RSCAS 2010/25

[3] Smart Grids European Technology Platform [Online]. Available: http://www.smartgrids.eu/

[4] F.W. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, M. Eijgelaar, "The role of natural gas in smart grids", *Journal of Natural Gas Science and Engineering 3*, 2011, pp. 608-616.

[5] D. Haeseldonckx, L. Peeters, L. Helsen and W. D'haeseleer, "The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions", *Renewable & Sustainable Energy Reviews 11*, 2007, pp. 1227-1243.

[6] F. Rahimi, A. Ipakchi, "Demand Response as a Market Resource Under the Smart Grid Paradigm", *IEEE Transactions on Smart Grid*, 1(1), 2010, pp. 82-88.

[7] B. Wille-Haussmann, T. Erge, C. Wittwer, "Decentralised optimisation of cogeneration in virtual power plants", *Solar Energy*, 84(4), 2010, pp. 604-611.

[8] G. Krajačića, N. Duića, Z. Zmijarevićc, B. Vad Mathiesend, A. A. Vučinića, M. da Graça Carvalho, "Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction", *Applied Thermal Engineering*, Vol. 31, Issue 13, 2011, pp. 2073-2083.

[9] A. Campos Celador, M. Ordiozola, J.M. Sala, "Implications of the modelling of stratified hot water storage tanks in the simulation of CHP plants", *Energy Conversion and Management 52*, 2011, pp. 3018-3026.

[10] K. Voorspools, W. D'haeseleer, "The impact of the implementation of cogeneration in a given energetic context", *IEEE transactions on energy conversion*, Vol. 18, No. 1, March 2003, pp. 135-141

Authors contacts:

Jeroen Vandewalle, Nico Keyaerts and William D'haeseleer (corresponding author)

University of Leuven (KU Leuven) Energy Institute

Mechanics and Energy Conversion (TME)

Celestijnenlaan 300A P.O Box 2421

B-3001 Heverlee

Belgium

Email : William.Dhaeseleer@mech.kuleuven.be

European
University
Institute
European University Press