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# FEASIBILITY AND PRIMARY ENERGY SAVINGS OF ABSORPTION CHILLERS FOR DATA CENTERS, BOTH DIRECT FIRED AND IN TRIGENERATION

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## ABSTRACT

Depending on the operating conditions, combined heat, cooling and power systems (CHCP) can sometimes compete energetically and economically with classical vapour compression chillers. Conclusions are often different if either the economic or energetic feasibility is investigated. The application of free chilling can highly affect the results.

In this paper, simulations in TRNSYS are performed of a cooling installation of a datacenter of 1500 kW. The use of absorption chillers with gas engines is compared with the application of superchillers (air cooled vapour compression chillers that can run in free chilling). Both single effect and double effect, direct and hot water fired absorption chillers have been studied. The impact of the variation of some crucial parameters on the economic and energetic feasibility of trigeneration is studied.

Concerning energetic feasibility, the efficiency of the gas engines and the temperature regimes are some crucial parameters. Varying energy prices highly affect the economic feasibility of trigeneration.

## INTRODUCTION

Until today vapour compression chillers are mostly used for cooling applications. However when heat is available as a by-product of another process, absorption chillers can be a viable alternative. Combining an absorption chiller with a cogenerator results in a combined heat, cooling and power system (CHCP). CHCP can be interesting in places with a simultaneous electricity, heat and cooling demand, such as hospitals and datacenters.

In Belgium, there are CHCP installations in the AZ Sint-Jan hospital in Bruges [4] and in the Berlaymont building in Brussels [5]. In the world other examples can be found in the Missisipi State University [6], Langenau in Germany [1], Skive in Denmark [7], the EURAC building in Bolzano (Italy) [1], the printing office Giesecke und Devriendt in Mnchen (Germany) [8], etc.

When one wants to evaluate and improve the performance of CHCP systems, a good model of the installation can provide insight in its behaviour. Generally, two types of models can be found in literature: steady state models and transient models.

Ziher et al. (2006) [2] describe a steady state analysis of the use of trigeneration in a hospital in Slovenia. In the article, vapour compression chilling is compared with a single-stage and two-stage absorption chiller in combination with a gas engine.

## NOMENCLATURE

| | |
|---|---|
| CHCP | Combined Heat, Cooling and Power |
| COP | Coefficient Of Performance (-) |
| eDCIE | Primary Energy Data Center Infrastructure Efficiency (-) |
| PDL | Part Design Load (-) |
| PEC | Primary Energy Consumption (GWh/year) |
| SEC | Site Energy Consumption (GWh/year) |
| TCO | Total Cost of Ownership (M€) |

*Symbols*

| | |
|---|---|
| $c_{el}^{buying}$ | Specific electricity cost for buying (c€/kWh) |
| $c_{el}^{selling}$ | Specific electricity cost for selling (c€/kWh) |
| $c_{gas}$ | Specific gas cost (c€/kWh) |
| $c_p$ | Specific heat capacity (kJ/kgK) |
| $\dot{m}$ | Massflow (kg/s) |
| $\dot{P}$ | Electric power ($kW_{el}$) |
| $\dot{Q}$ | Thermal power ($kW_{th}$) |
| $R_{act}$ | Actualisation rate (%) |
| $R_{elec}$ | Actualisation rate for specific electricity cost (%) |
| $R_{gas}$ | Actualisation rate for specific gas cost (%) |

*Greek symbols*

| | |
|---|---|
| $\eta$ | Efficiency (-) |

*Subscripts*

| | |
|---|---|
| chw | Chilled water |
| coolingload | Coolingload |
| cw | Cooling water |
| el | Electric |
| hw | Hot water |
| in | Inlet |
| out | Outlet |
| ref | Reference |
| th | Thermal |

Fumo et al. (2008) [3] use two evaluation criteria to evaluate the economical and ecological feasibility of trigeneration in steady-state: the site energy consumption (SEC), representing the energy consumption on-site, and the primary energy consumption (PEC), being the SEC and the energy consumption of the generation of the extra power bought. The article concludes that the SEC of trigeneration is generally larger than the SEC of a classical installation, because of the extra energy consumption of the cogenerator. Conversely, in their analysis the PEC of trigeneration is generally smaller than a classical installation. The article concludes that this difference in results using either SEC or PEC is the cause of the difference in economical and ecological feasibility of trigeneration.

The opinion of the authors of this paper is that the financial feasibility should not be evaluated using PEC or SEC, but with a thorough economical analysis, taking into account the difference in gas price and electric power price, the variation of the gas and electric power prices over time and the influence of a variation of the gas price on the variation of the electric power price. Secondly, a steady state analysis doesn't take into account the seasonal influences and the variation of part load behaviour of chillers, cogenerators and cooling towers caused by these seasonal variations.

Zogou et al. (2007) [9] describe a complex transient analysis in TRNSYS of a trigeneration installation in the Volos Public Hospital, and make a thorough financial analysis to be able to assess the economical feasibility. In this case trigeneration wasn't feasible if the installation was running at nominal values.

Napolitano et al. (2009) [1] analyse the trigeneration installation in the EURAC building in Bolzano using TRNSYS, comparing it with a classical solution with vapour compression chillers. This study concluded that the primary energy consumption of the trigeneration was larger, but that the operating cost was smaller.

Calise et al. (2009) [10] made a similar analysis using TRNSYS, also resulting in different conclusions concerning either economical or ecological feasibility.

This clearly shows that a transient analysis is needed to take seasonal variations into account. Moreover, conclusions can be different from case to case. In none of the stated articles the influence of the application of free chilling is studied. However the study presented in this article will demonstrate the high influence of free chilling on the results.

## GENERAL DESCRIPTION OF THE SIMULATIONS

### Simulations with superchillers

Figure 1 shows a simplified scheme of the model of the superchiller installation. The installation consists of two parallel cycles with chilled water, system ”‘A”’ and system ”‘B”’, to ensure a high redundancy. In each system, two superchillers (759 $kW_{th}$ nominal capacity) are connected in parallel.

### Simulations with hot water fired absorption chillers

Figure 2 visualises the simplified scheme of the simulations with hot water fired absorption chillers. The same scheme is used for single and double stage chillers. There are three main cycles: a hot water cycle, a cooling water cycle and a chilled water cycle.

When free chilling is applied (this is only possible when the ambient air temperature is sufficiently lower than the chilled water temperature), the absorption chiller and gas engines are shut down, and the chilled water is directly chilled by the cooling water in a heat exchanger.

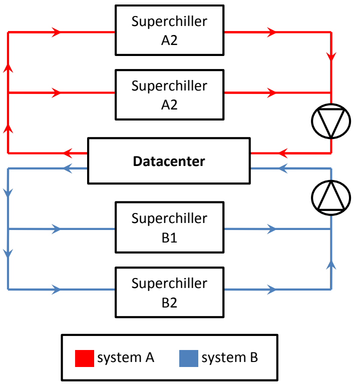

Figure 1. Description of the simulations with superchillers

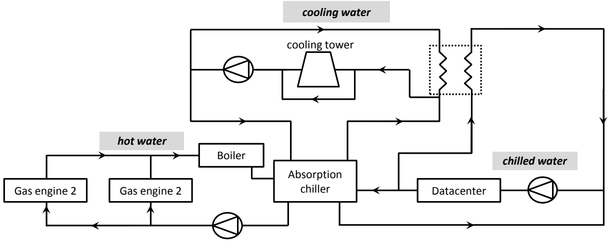

Figure 2. Description of the simulations with hot water fired absorption chillers

### Preconditions in this study

The simulations are performed using a number of preconditions, affecting the results.

*Preconditions about the coolingload*

In this study a near constant coolingload is adopted. The coolingload of a datacenter can be modelled as a constant load because nearly all electric energy of the datacenter is transformed into waste heat. The influence of the weather on the coolingload is neglected as well.

*No supplementary heat demand*

It is presumed that there is no supplementary heat demand besides the absorption chillers. As a consequence the gas engines need to be shut down when the absorption chillers aren't running.

### Simulations with direct fired absorption chillers

As figure 3 shows, the scheme for the simulations with direct fired absorption chillers is very similar to that of the simulations with hot water fired chilles (figure 2). In these simulations, the hot water cycle doesn't exist. Instead, the exhaust gases of the gas engines are injected directly in the chillers.

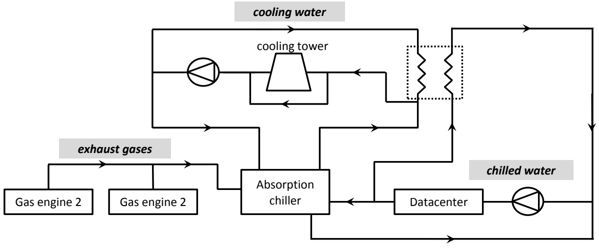

Figure 3. Description of the simulations with direct fired absorption chillers

## DESCRIPTION OF THE USED MODELS

This paragraph provides a more detailed explanation about the modelling of used components, being:

- the datacenter
- the gas engines
- the chillers.

### Model of the datacenter

The datacenter is modelled as a ”black box”. The cooling load $\dot{Q}_{coolingload}$ $(kW_{th})$ of a whole year is listed in a datafile. The chilled water outlet temperature $(T_{chw,out})$ is calculated with that coolingload $(\dot{Q}_{coolingload})$, the heat capacity $(c_{p,chw})$, mass flow $(\dot{m}_{chw})$ and inlet temperature $(T_{chw,in})$ of the chilled water:

$$T_{chw,out} = \frac{\dot{Q}_{coolingload}}{c_{p,chw} \cdot \dot{m}_{chw}} + T_{chw,in} \tag{1}$$

Because the studied datacenter is still being built, there is a lack of measuring data of the cooling load. That’s why a general profile visualised in 4 is used in this paper.

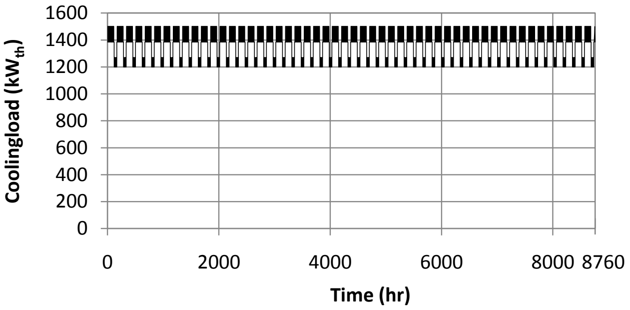

Figure 4. Year profile of the coolingload of the datacenter

### Model of the gas engines

TRNSYS doesn’t provide a gas engine model. An own model is used, calculating the part load of the engines (PDL) in function of the heat demand. In a datafile, electric and thermal power $(\dot{P}$ and $\dot{Q})$ and efficiency $(\eta_{el}$ and $\eta_{th})$ are listed in function of the part load (PDL). An important remark is that the useful thermal power of the gas engines in combination with a direct fired absorption chiller will be smaller than the useful thermal power of the same gas engines in combination with a hot water fired absorption chiller, because in the former case the heat of the jacket cooling water can’t be recovered.

Table 1 provides a list of the used gas engines in the simulations. Figure 5 illustrates the part load behaviour of a gas engine in combination with a hot water fired chiller and figure 5 illustrates the part load behaviour of the same engine in combination with a direct fired chiller, showing the drop in recuperable thermal power and thermal efficiency.

Table 1. Choice of the gas engines

| **Simulation type** | **Gas engines** |
|---|---|
| Single effect direct fired | 2 x JEN JMS616GS-NLC |
| Single effect hot water fired | 2 x JEN JMS316GS-NLC |
| Double effect direct fired | 2 x JEN JMS316GS-NLC |
| Double effect hot water fired | 2 x JEN JMS316GS-NLC |

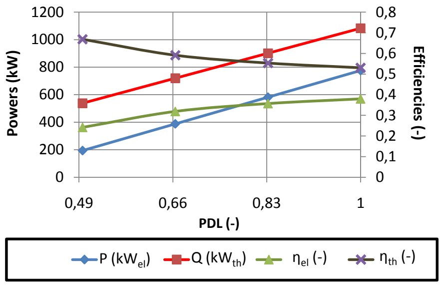

Figure 5. Part load behaviour of gas engine JEN JMS316GS-NLC in combination with a hot water fired chiller

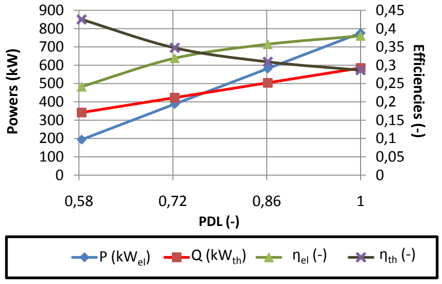

Figure 6. Part load behaviour of gas engine JEN JMS316GS-NLC in combination with a direct fired chiller

### Models of the absorption chillers

Table 2 lists the absorption chillers used in the four simulation types.

To model the hot water fired absorption chillers (both single effect and double effect), the standard TRNSYS Type 107 is used. Catalogue part load data [11] is used, providing the chiller’s capacity and fraction of nominal design energy input (PDEI) in function of the part load (PDL), cooling water temperature, chilled water temperature and hot water temperature.

To model single effect direct fired chillers, the standard TRNSYS Type 681 is insufficient. This standard model doesn’t take into account that the capacity of the chiller varies in function of part load, chilled water temperature and cooling water temperature.

To model double effect direct fired chillers, the standard TRN-

Table 2. Choice of the absorption chillers

| **Chiller type** | **Chiller data** |
|---|---|
| Single effect direct fired | 2 x Broad BDE 75<br>$\dot{Q}_{nom}$ = 872 $kW_{th}$<br>$\text{COP}_{\text{nom}}$ = 0.79 |
| Single effect hot water fired | 1 x Broad BDH 150<br>$\dot{Q}_{nom}$ = 1535 $kW_{th}$<br>$\text{COP}_{\text{nom}}$ = 0.76 |
| Double effect direct fired | 1 x Broad BE 150<br>$\dot{Q}_{nom}$ = 1745 $kW_{th}$<br>$\text{COP}_{\text{nom}}$ = 1.41 |
| Double effect hot water fired | 1 x Broad BH 150<br>$\dot{Q}_{nom}$ = 1745 $kW_{th}$<br>$\text{COP}_{\text{nom}}$ = 1.41 |

SYS Type 678 is insufficient as well. This model doesn't take into account that the fraction of nominal energy input (PDEI) varies in function of the chilled water temperature.

To solve these problems, an own TRNSYS model is made, modelling direct fired absorption chillers (both single effect and double effect). Catalogue data of absorption chillers [11] is used, providing the chiller's capacity in function of cooling water temperature and chilled water temperature, and the fraction of nominal energy input (PDEI) in function of part load (PDL), cooling water temperature and chilled water temperature.

### Model of the superchillers

To model the superchillers, the standard TRNSYS Type 655 is used. To take into account that these chillers can run in free chilling, a bypass of the Type 655 is included with a heat exchanger and an axial fan. Air provided by the axial fan directly cools the chilled water flowing in the coils of the heat exchanger. To model part load behaviour, catalogue data of superchillers is used [12].

## COMPARISON METHOD

The performance of the installations is analyzed using three different parameters: the primary energy consumption (PEC), the Primary Energy Data Center Infrastructure Efficiency (eDCIE) and the Total Cost of Ownership (TCO).

### Primary Energy Consumption (PEC)

When calculating the Primary Energy Consumption (PEC), a reference efficiency of 40 % is taken into account to quantify the primary energy use of electricity bought on the grid [14].

### Primary Energy Data Center Infrastructure Efficiency (eDCIE)

The Primary Energy Data Center Infrastructure Efficiency (eDCIE) is equal to the ratio of the electricity demand of the servers and the total primary energy consumption of the data center and the cooling installation.

### Total Cost of Ownership (TCO)

To calculate the Total Cost of Ownership (TCO), an actualisation rate $R_{act}$ of 3 %, a specific gas price $c_{gas}$ of 4.3 c€/kWh, and specific electricity prices of 11 c€/kWh (buying) and 5.4 c€/kWh (selling) are used [15]. The Total Cost of Ownership (TCO) is calculated over a period of 15 years, being a representative lifespan of a gas engine [13]

Table 3 gives a summary of the used boundary conditions in the simulations.

In the comparison, **free chilling** is activated in the installation with superchillers as the application of free chilling is a characteristic of this type of chillers. In the installations with absorption chillers free chilling isn't applied, because free chilling has a very high influence on the results. The following comparisons and parametric analysis want to study the behaviour of the trigeneration installations specifically without free chilling. Subsequently, the influence of free chilling is investigated in a seperate study.

## NOMINAL COMPARISON

To be able to properly understand the results, good insight in the energy flows is important. The studied trigeneration installation (cooling installation and datacenter) can be visualised as a ”‘black box”' as in figure 7. The installations has a cooling demand as the datacenter needs to be cooled. There is a demand for electric energy as well (of the datacenter and the cooling installation). To comply to those needs, an input of natural gas is needed to feed the gas engines. If the gas engines don't produce enough electric energy, a supplementary ammount of electric energy needs to be bought on the grid.

Table 3. Boundary conditions

| Parameter | Value |
|---|---|
| Cooling water regime | 30°C / 36°C |
| Hot water regime | 98°C / 83°C (single effect)<br>180°C / 165°C (double effect) |
| Chilled water regime | 10°C / 15°C |
| $\eta_{\text{el,ref}}$ | 0.4 |
| $c_{\text{el}}^{\text{buying}}$ | 11 c€/kWh |
| $c_{\text{el}}^{\text{selling}}$ | 5.4 c€/kWh |
| $c_{\text{gas}}$ | 5.4 c€/kWh |
| $\text{R}_{\text{act}}$ | 4 % |
| $\text{R}_{\text{gas}}$ | 5 % |
| $\text{R}_{\text{elec}}$ | 5 % |

Figure 7. Blackbox representation of trigeneration installation

**A lower COP** of the chillers will result in a higher heat demand to the gas engines for the same coolingload. The gas engines will run less in part load, and the input of natural gas will rise. The electric energy produced by the gas engines will rise as well, resulting in a drop of the supplementary ammount of electric energy bought on the grid.

**A higher COP** of the chillers result in the contrary. The heat demand to the gas engines will be lower, letting the gas engines run more in part load. As a result the input of natural gas will drop, but the electric energy produced by the gas engines as well, resulting in a rise of the supplementary ammount of electric energy bought on the grid.

As figure 8 illustrates, the primary energy consumption (PEC) of the installation with superchillers and the installation with a single effect hot water fired absorption chiller are the lowest and are comparable. The PEC of the installation with a double effect direct fired chiller is a little higher, followed by the double effect hot water fired chiller and the single effect direct fired chiller.

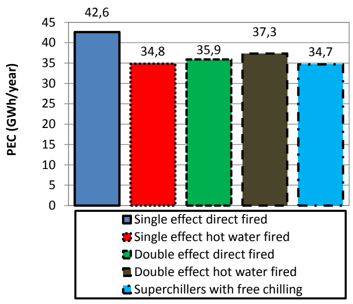

Figure 8. Nominal comparison with PEC (GWh/year)

The installation with a single effect direct fired chiller has a higher primary energy consumption (PEC) because here a low COP of the chillers is combined with a low thermal efficiency of the gas engines (as the heat of the jacket water can't be recuperated when the gas engine is used with a direct fired chiller). This results in a higher heat demand for the same coolingload, and this heat is produced with a lower efficiency. The high PEC of the installation with a double effect hot water fired is due to the high ammount of supplementary electric energy bought on the grid, as the combination of a high COP and a high gas engine efficiency results in a low production of electric energy.

The installations can be compared using the eDCIE (figure 9) and TCO (figure 10) resulting in similar conclusions.

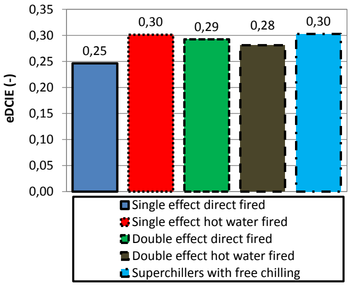

Figure 9. Nominal comparison with eDCIE (-)

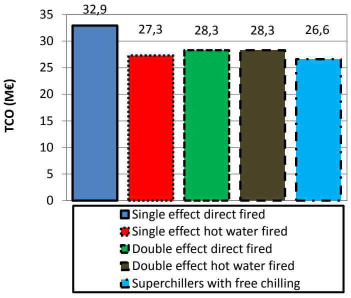

Figure 10. Nominal comparison with TCO (M€)

## SENSITIVITY ANALYSIS

### Technical parameters

#### *Effiencies of the gas engine*

Selecting gas engines with a high electric and thermal efficiency is of the utmost importance in trigeneration installations. The impact of the electric and thermal efficiency on the PEC, eDCIE and TCO is very high. Figure 11 demonstrates the impact of the electric efficiency on the PEC and 12 illustrates the impact of the thermal efficiency on the PEC.

The higher the relative ammount of the primary energy use of the gas engines in the total primary energy consumption PEC, the higher the impact of the gas engine efficiencies will be.

#### *COP of the absorption chillers*

One would expect that a higher COP of the absorption chiller would result in a lower PEC, a higher eDCIE and a lower TCO. That isn't always true. Based on the coolingload, the heat demand can be calculated using the COP. That heat demand sets the part load ratio of the gas engines. Those engines generate heat, and electric energy as byproduct. When more electric energy is produced than consumed on-site, the surplus is sold. When less electric energy is produced than consumed on-site, supplementary electric energy is bought.

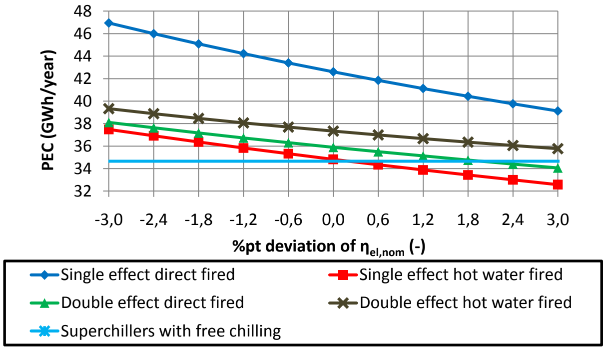

Figure 11. Impact of the electric efficiency of the gas engines on PEC (GWh/year)

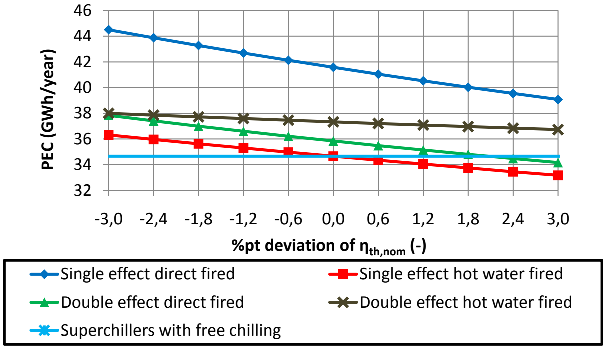

Figure 12. Impact of the thermal efficiency of the gas engines on PEC (GWh/year)

A lower COP results in a higher heat demand for the same coolingload.

1. A higher heat demand results in a higher primary energy consumption of the gas engines
2. With a higher heat demand, the load of the gas engines is higher, resulting in a lower thermal efficiency, raising the primary energy consumption of the gas engines
3. With a higher heat demand, more electric energy is produced on-site. The more electric energy produced on-site, the less electric energy needs to be bought, resulting in a drop of PEC

The combined effect of those factors will set the impact of the COP. Figure 13 shows that for the installations with hot water fired absorption chillers, a lower COP results in a lower primary energy consumption PEC.

#### *Temperature regimes*

Consequently, temperature regimes resulting in a higher COP of the absorption chiller will raise the total primary energy consumption (PEC). Temperature regimes triggering a lower COP of the absorption chiller will reduce the PEC. Temperature regimes resulting in a lower COP are:

- A lower chilled water temperature (without free chilling)
- A higher cooling water temperature
- A lower temperature of the heat source

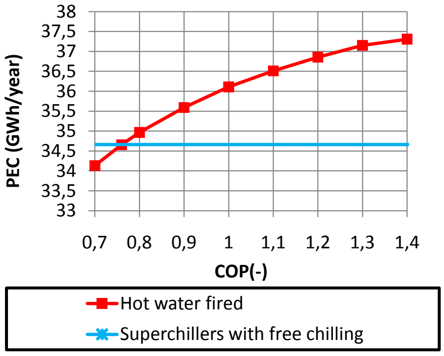

Figure 13. Impact of the COP on the PEC of the installations with hot water fired chillers (GWh/year)

Figure 14 illustrates the mentioned behaviour for the impact of the chilled water regime on the primary energy consumption (PEC) of the installation with a single effect hot water fired chiller.

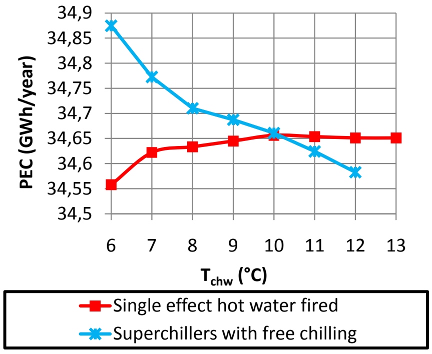

Figure 14. Impact of the chilled water regime on the PEC of the installation with a single effect hot water fired chiller (GWh/year)

### *Reference efficiency for the supplementary bought electric energy*

Figure 15 illustrates the impact of the reference efficiency for the production of the supplementary bought electric energy on the PEC of the installations. This figure demonstrates the high impact of this chosen efficiency on the results. The higher the ammount of electric energy bought, the higher the impact of this efficiency. As the impact on the PEC of the installation with superchillers is the largest, a lower value of this reference efficiency will favour trigeneration.

### *Free chilling*

Free chilling is possible when the ambient temperature is lower than the chilled water setpoint temperature for a considerate ammount of time. The higher the chilled water setpoint temperature, the more free chilling is possible in the span of a year. Applying free chilling in trigeneration installations has a number of consequences.

1. The primary energy consumption of the gas engines will drop as in free chilling the gas engines are shut down (because the absorption chillers don't need heat)
2. The consumed electric energy will drop
3. The produced electric energy will drop as the gas engines are being shut down for an ammount of time

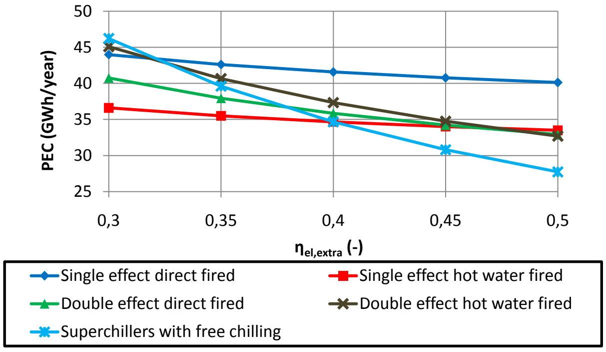

Figure 15. Impact of reference efficiency for the supplementary bought electric energy on PEC (GWh/year)

4. When the drop of produced electric energy is larger than the drop of consumed electric energy, more electric energy will need to be bought.

As figure 16 demonstrates, free chilling has a very high impact on the primary energy consumption (PEC) of the installations. With free chilling, the PEC will rise when applying a lower chilled water regime, whereas without free chilling the PEC would drop as demonstrated earlier.

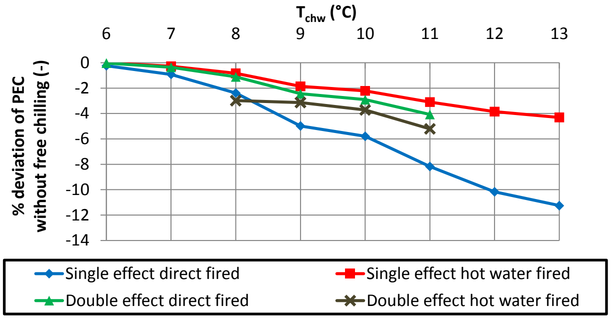

Figure 16. Impact of chilled water regime with free chilling on deviation of PEC without free chilling

## Market parameters

### *Specific electricity cost*

Figure 17 illustrates the impact of the variation of specific electricity cost on the Total Cost of Ownership (TCO) of the investigated installations. The larger the ammount of electricity bought, the larger this impact will be. This explains the high impact on the TCO of the installation with superchillers and the low impact on the TCO of the installation with a single effect hot water fired absorption chiller.

### *Specific gas cost*

As figure 18 illustrates, the specific gas cost has a very high influence on the Total Cost of Ownership (TCO) of the trigeneration installations as well. A drop of 5 % of the specific gas cost (from 4.3 c€/kWh to 4.08 c€/kWh would make the TCO of the installation with a single effect hot water fired absorption chiller lower than the TCO of the installation with superchillers.

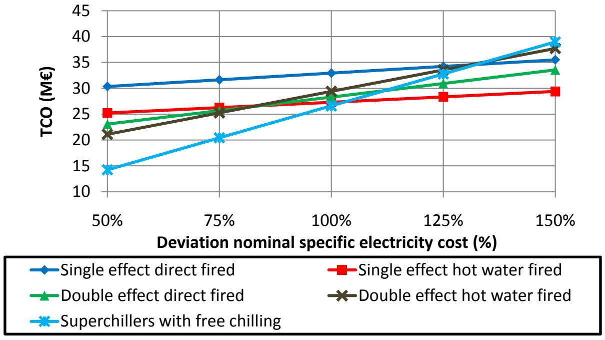

Figure 17. Impact of specific electricity cost on Total Cost of Ownership (TCO) of the installations

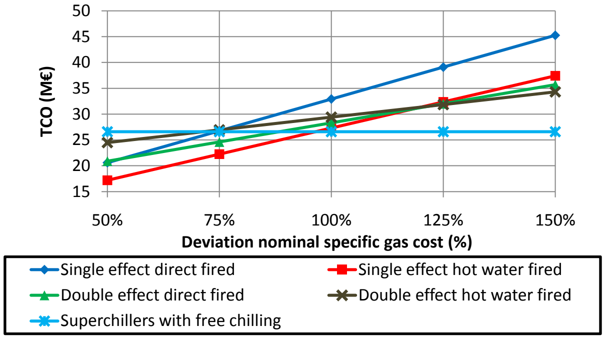

Figure 18. Impact of specific gas cost on Total Cost of Ownership (TCO) of the installations

*Specific electricity cost coupled with specific gas cost*

A market study for the Belgian market [13] has demonstrated that a rising specific gas cost triggers a raise of the specific electricity cost. More specifically, the study concluded that the raise of the specific electricity cost in general is 2.2 times the raise of specific gas cost. Figure 19 illustrates the impact when this coupling of the specific gas and electricity cost is applied. The gradients are similar for all investigated installations, making the influence of the specific costs on the variation of TCO between the installations a lot smaller. The gradients are similar because the ammount of bought electric energy compared to the ammount of bought natural gas has a smaller influence in this case than in the case where specific electricity and gas cost are varied independently, as in this particular case both the specific electricity and gas cost are varied simultaneously.

## CONCLUSIONS

When the installations are compared on nominal values, the primary energy consumption (PEC) and Total Cost of Ownership (TCO) of the installation with superchillers are the lowest (and the eDCIE the largest), but very comparable to the PEC, TCO and eDCIE of the installation with a single effect hot water fired chiller.

It's very important to select gas engines with a high electric and thermal efficiency, because of the large impact of the gas engine's electric and thermal efficiency on the PEC, TCO and eDCIE of the installations.

Installations with an absorption chiller with a lower COP generally will have a lower PEC, a lower TCO and a higher eDCIE.

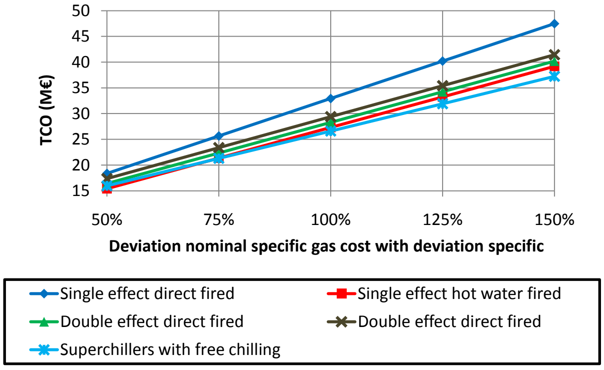

Figure 19. Impact of specific electricity cost coupled with specific gas cost on Total Cost of Ownership (TCO) of the installations

Temperature regimes triggering a lower COP will result in a lower PEC, a lower TCO and a higher eDCIE. Temperature regimes resulting in a lower COP are:

- A lower chilled water temperature (without free chilling)
- A higher cooling water temperature
- A lower temperature of the heat source

The impact of the chosen value of the reference efficiency of bought electricity on the primary energy consumption (PEC) is very large, making this value very important when assessing the feasibility of trigeneration.

Applying free chilling will result in a drop of the primary energy consumption (PEC), and this drop will be larger when higher chilled water setpoint temperatures are used. When using free chilling, the PEC of the trigeneration installations will rise when lower chilled water setpoint temperatures are used, whereas without free chilling lowering the chilled water setpoint temperature would result in a drop of PEC.

Varying the specific electricity cost and the specific gas cost independently result in a very high impact on the TCO of the investigated installations, but when the specific electricity cost and specific gas cost are varied together, the impact on the TCO is very similar for all investigated installations, making the impact on the difference in TCO of the installations smaller.

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