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Reinventing hot water? Towards optimal sizing and management of cogeneration: A case study for Belgium

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Abstract

Expectations are high for cogeneration (the joint generation of heat and power) to support solutions for energy-related problems and climate issues. The sizing, i.e., the rated thermal and electric power, of cogeneration units, is currently largely based on simple static criteria in which the output of a cogeneration units is maximised for a given or estimated heat-demand profile.

In this paper, we investigate the validity of this sizing strategy. Firstly, we develop a methodology to objectively evaluate the impact of the use of cogeneration on the overall primary-energy use and greenhouse-gas emissions. To do so, we compare two scenarios; a base case without additional cogeneration in which heat is provided by boilers and all electricity comes from the central power system and an alternative scenario with cogeneration where the heat is delivered by the cogeneration, if necessary supported by back-up boilers, and where the cogeneration also takes over part of the electricity demand formerly delivered by the central power system. The major advantage of our method is that we fully take into account the dynamic interaction between the cogeneration and the central power system by scrupulously simulating the power generation on an hourly basis and a sub-power-plant level. As such, we can detect possible sub-optimal dispatching of the central power system caused by the non-dispatchable and possibly fluctuating output of the cogeneration.

Apart from the conventional sizing strategy of cogeneration, we look at alternative options where the interaction with the central power system is improved. A first possibility is to use smaller cogeneration, i.e., reduced-scale sizing, that can deliver a smaller share of the thermal energy but that can operate with a higher annual use. A second possibility considered is the extension of the use of the cogeneration without reducing the scale, which implies that part of the heat cannot be used. This option is called partial-heat-usage sizing.

To illustrate our method and its use for optimal sizing of cogeneration, we look at the cogeneration in the service sector in the Belgian energetic context towards 2010. We find that both the reduced-scale sizing and the partial-heat-usage sizing can lead to significantly higher primary-energy savings and emission reductions.

Keywords: Cogeneration; Sizing; Simulation; Power generation

1. Introduction

In energy markets evolving towards lower CO_2 emissions, some countries partly count on the massive use of cogeneration. Cogeneration combines the generation of electricity and heat with an improved overall energy-conversion rate compared to the separate generation of the same amounts of heat and electricity.

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In estimating the savings in primary-energy use and CO_2-emission reduction possible by using cogeneration, most regulatory instruments (such as national allocation plans and CHP-certificate schemes) use simplified *static* formulas, in which the potential cogeneration units are compared to hypothetical boilers and reference power plants providing the same amount of energy. The literature shows that these simple rules of thumb lead to acceptable results for cogeneration units with a high annual use, e.g., for industrial purposes. For applications with a lower utilisation, e.g., for space-heating purposes, the simple static formulas may lead to considerable errors when compared to the actual primary-energy savings and emission reductions.

In the static logic, the sizing of cogeneration units, i.e., the choice of the rated thermal and electric power of the cogeneration device, is currently based on the simple rule that the cogeneration device should generate the largest possible share of the total heat demand. This is translated via the largest possible rectangle inscribed in the load-duration curve of the heat demand (as explained in Section 4.1). Furthermore, there is also an at first sight equally logic rule that it is forbidden to "waste" part of the heat that is generated by the cogeneration.

In this paper, we argue that those simple rules based on the static logic cannot be sustained in reality. Including the overall dynamics of the electricity-generation system, we use a general method in which the primary-energy savings and CO_2-emission reduction of specific cogeneration applications can be determined precisely. In this process, we present a methodology to optimise the sizing of a cogeneration unit for a specified heat demand. We also look at the operating conditions of the cogeneration unit by prolonging its operation time whereby part of the heat cannot be used.

The aim of the paper is to objectively determine the optimal cogeneration size for a given heat demand. We first discuss our evaluation method for cogeneration. Then, we look at the optimisation of the sizing and the utilisation duration of cogeneration. As an example to illustrate our method, we use cogeneration in the service sector.

2. Evaluating the quality of cogeneration

The so called "quality" of the joint generation of heat and power is evaluated by looking at the primary-energy savings or the emission reduction achieved by using cogeneration compared to separate generation.

2.1. Evaluation method for evaluating the quality of cogeneration

2.1.1. Description of the dynamic evaluation method

In earlier papers [1,2], we have already demonstrated that static formulas may lead to large errors in quality calculation of cogeneration, especially for cogeneration with limited annual use as is, e.g., the case for space-heating applications. An objective dynamic evaluation method was presented to include the impact of the, possibly intermittent, output of the cogeneration units on the operation

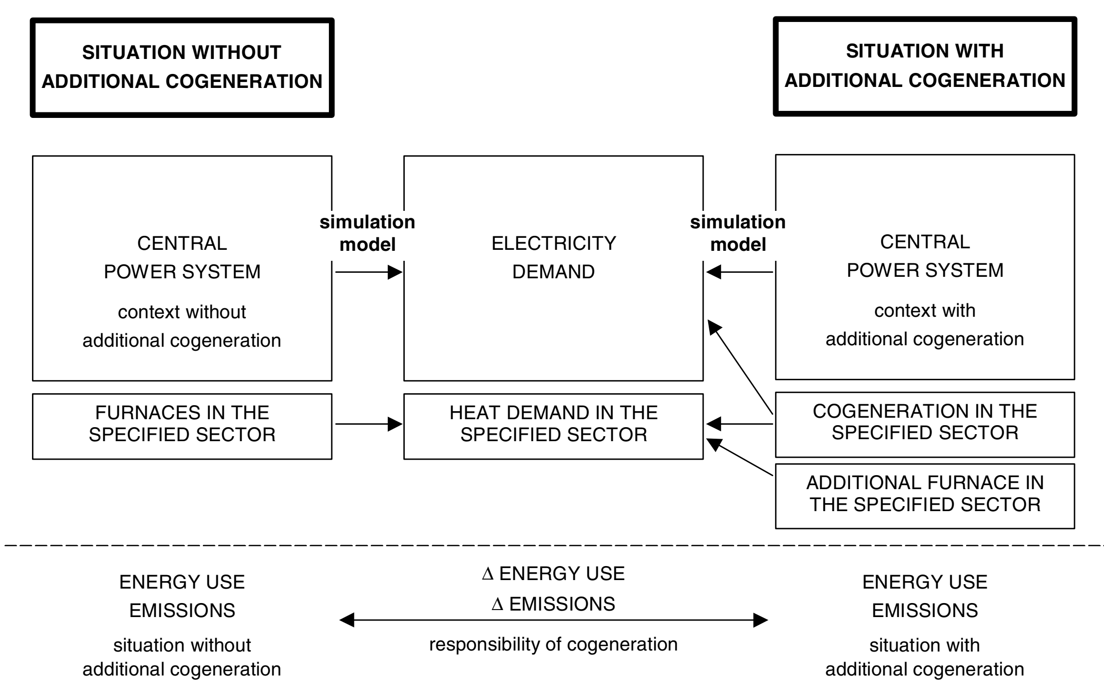

Fig. 1. Method for the evaluation of cogeneration. The scenario on the left hand side is the base case without additional cogeneration. The scenario on the right hand side is the alternative scenario with additional cogeneration. In both scenarios, the same energy—heat and electricity—is delivered (see [1,2] for more details).

of the central power system. The comprehensive dynamic evaluation method is shown schematically in Fig. 1. The real impact of the use of cogeneration is obtained by comparing two scenarios; a *base-case* scenario in which no additional cogeneration is used and an *alternative* scenario with a given amount of additional cogeneration. For an elaborate discussion of this evaluation method using dynamic simulations, we refer to [1].

The operation of the central power system is simulated with the simulation tool PROMIX. As PROMIX is not commercially available, its use, input and output are briefly explained here. For a more elaborate discussion of PROMIX and some application examples, we refer to [3].

2.1.2. The power-system simulation tool PROMIX

PROMIX simulates the response of an electric power system subject to a given power demand.

The power system used in PROMIX consists of different separate power plants. A plant can be operated at every level between its minimum-operation point and full load. Apart from the minimum-operation point, PROMIX also considers other technical restrictions of power plants such as the minimum up time and the minimum down time of a plant. Also, the fuels that can be used in the plants are specified. If different fuels are possible in a particular plant, PROMIX selects the most economic option.

The fuel properties in PROMIX are the emissions and the prices. The fuel prices are further on used to optimally dispatch the power generation to the demand.

The power demand is given on an hourly basis. Since PROMIX is intended to be used on a country level, the possible cross-border interactions need to be implemented exogenously.

PROMIX itself simulates the most economic dispatching of the power system on an hourly basis, while respecting the technological restrictions of the individual power plants (e.g., output-related primary-energy use or the instantaneous efficiency, and the already mentioned minimum-operation point, minimum up and down time). The output of PROMIX consists of the electric power generated by each separate power plant on an hourly basis (i.e., for all 8760 h/a), as well as the corresponding energy use, primary-energy costs and emissions.

2.2. Error in using static formulas

In the static evaluation of cogeneration, mostly static simplified methods are used in which the cogeneration unit is compared to a fictitious boiler and power plant providing the same amount of heat and power.

The most important reason for the failure of this method is that it completely neglects the dynamics of power generation. Usually, the cogeneration unit is considered to be heat driven, which implies that it is only activated when sufficient heat is needed. When heat demand is lower than the lowest partial-load level of the cogeneration unit, it is off-line. When the heat demand varies considerably, e.g., as is the case when cogeneration is used for space-heating purposes, the electric power output of the cogeneration unit will fluctuate accordingly. An electric power plant, on the other hand, is dispatched independently of the heat demand. Moreover, a new and highly efficient power plant, will probably have a fairly constant utilisation level. Therefore, when heat demand is not constant, electricity originating from cogeneration (fluctuating according to heat demand) should not be compared to electricity from a power plant (fairly constant and determined by central dispatching).

3. Application example; cogeneration in the service sector

As an example throughout this paper, we use cogeneration in the service sector. The heat demand for this sector was composed by Martens and Dufait [4] and contains heat profiles of offices, education and research institutions, hospitals, shops, hotels and catering industry, sports and culture centres, laundry services and other services. A typical aggregate chronological heat demand profile for the service sector is shown in Fig. 2. This profile is clearly dominated by space heating; heat demand is large in winter and small during the summer. Since some of the applications (e.g., offices and shops) are typical weekday activities, there is also a distinct periodic dip in the heat demand every weekend.

The load-duration curve (sometimes referred to as the monotonic curve) of the same heat-demand profile is shown in Fig. 3. This load-duration curve arranges the heat-demand values starting with the largest value.

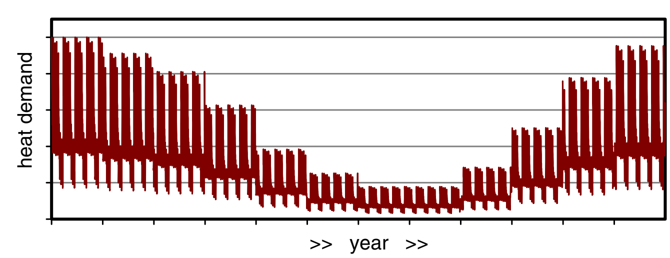

Fig. 2. Typical chronological heat-demand profile in the service sector. The horizontal axis covers a full year, the ordinate axis uses arbitrary normalised units.

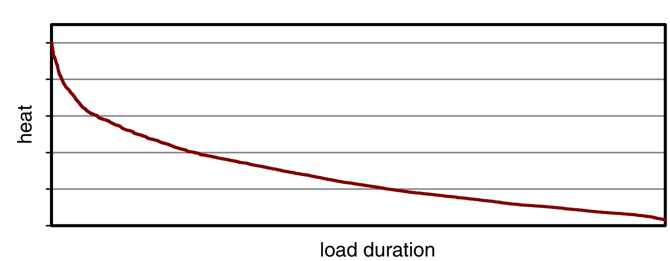

Fig. 3. Load-duration curve of the heat demand in the service sector according to the chronological profile of Fig. 2.

4. Sizing of cogeneration

The sizing of cogeneration refers to the choice in the rated electric and thermal power of the cogeneration unit.

4.1. ''Classic'' approach in the sizing of cogeneration

A common reasoning in the sizing of the thermal power of a cogeneration unit is to maximise its thermal output (electricity can only be generated when heat is needed). Indeed, if a cogeneration unit is labelled as ''qualitative'', based on the ''linear'' assumption that the primary-energy saving and the emission reduction can be optimised by maximising the output of the cogeneration device under the condition that none of the energy generated is wasted.

This sizing strategy is illustrated in Fig. 4A for the heat load-duration curve of the service sector. A given cogeneration unit with a rated thermal power is fitted in the load-duration curve. If the unit can only operate at full power without modulation, the annual heat output of that cogeneration unit is given by the rectangle shown in Fig. 4. Therefore, the dimension of a cogeneration unit is often chosen by fitting the ''maximum-rectangle'' in the load-duration curve considered.

For the aggregate heat-demand profile of the service sector shown in Fig. 2, the thermal power of the cogeneration unit fitting this ''maximum-rectangle'' is about 28% of the maximum heat load and the annual use is roughly 3700 h/a.

The classic approach of sizing of cogeneration facilities is discussed in AMPERE [5] and in [6]. General considerations on sizing of CHP units have been touched upon in the EDUCOGEN document [7], while different optimising considerations have been offered very recently by Beihong and Weiding [8].

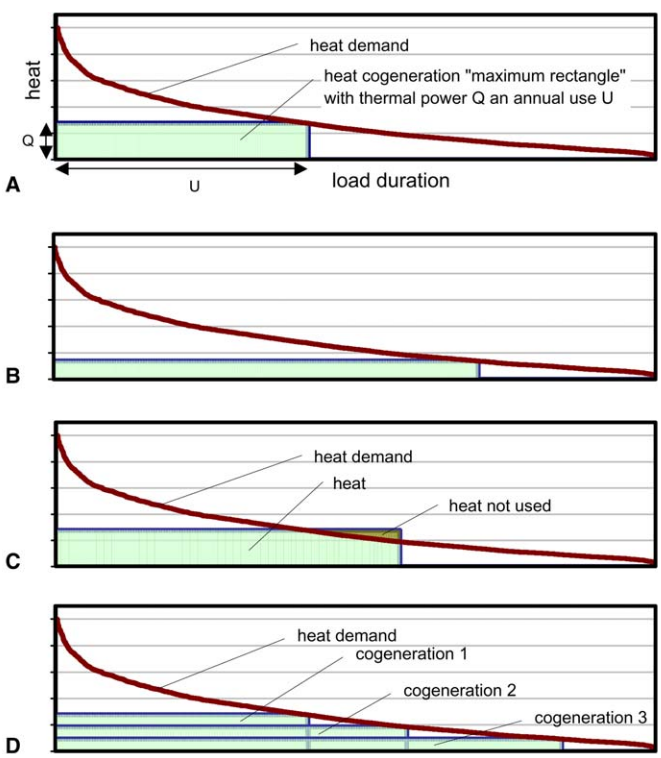

Fig. 4. Different sizing strategies for cogeneration. A is the ''classic'' sizing of cogeneration unit for a given heat demand load-duration curve. The rated thermal power Q of the unit is determined by the largest possible rectangle inscribed in the load-duration curve. The rated electric power of the device is determined through the Q/E ratios of the available cogeneration units. B applies to a smaller-scale cogeneration with a smaller heat generation but a higher annual use. C applies to the same cogeneration unit as in case A, but its use if extended to periods with lower heat demand. D applies to cogeneration sizing by using multiple units, three in this case.

4.2. Optimal sizing of cogeneration

Since the purpose of using cogeneration is to save primary energy and to reduce CO_2 emissions, it is more important to dimension cogeneration by maximising the really occurring energy savings or emission reduction rather than simply maximising its output as pursued in the ''maximum-rectangle'' rule.

The point is that, as we already hinted above, the quality of cogeneration not only depends on its intrinsic energy-conversion rates but also on its annual use and on the interaction with the central power system. In an earlier paper [1], we have found that, in many cases, the quality of cogeneration improves with increasing annual use because of a better and more optimal interaction with the central power system.

Therefore, in this paper, we look at different sizing options, starting from the ''maximum-rectangle'' rule but with an increase in annual use in an attempt to improve the quality of the cogeneration.

4.2.1. Reduced-scale sizing

One option is to reduce the size of the cogeneration unit as shown in Fig. 4B, whereby the rated thermal power of the cogeneration unit is diminished while the annual use is increased. Although the quality (if calculated properly, based on a dynamic evaluation) of the cogeneration should improve with this action, it is unclear what will happen to the really occurring overall benefits in energy savings and emission reduction. On the one hand, the benefits will increase because of the better dynamic interaction with the central power system. On the other hand, the benefits may decrease because the overall heat and power generation (in terms of total energy) from the cogeneration will diminish.

4.2.2. Partial-heat-usage sizing

A second option to increase the annual use of this cogeneration would be to extend its use to periods of lower heat demand and thus not using part of the heat generated. This approach is shown in Fig. 4C. The annual use of the cogeneration unit increases, but part of the heat generated is ''thrown away''. Here, we also have two effects that influence the benefits of the cogeneration. On the one hand, the quality improvement caused by the better interaction with the central power system will lead to higher energy savings. On the other hand, wasting part of the heat generated is unfavourable.

4.2.3. Other options

Apart from the two options discussed above, there are also other possibilities for increasing the annual use of cogeneration. These options are also mentioned for completeness, but are not further elaborated on in this paper in which we mainly focus on the methodology. Extending our sizing philosophy to those cases seems straightforward.

4.2.3.1. Heat storage. A commonly used option is the use of heat-storage buffers to level the operation of cogeneration units in time. When using the sizing strategy with partial heat usage as shown in Fig. 4C, it is possible to store that part of the heat that cannot be used directly and to later on use it to fill up part of the heat-duration curve (the white "triangles" in the second part of Fig. 4C). As such, the use of the cogeneration is extended without wasting part of the heat generated. (For a detailed explanation of the interaction of a cogeneration unit with a heat-storage buffer, see [6].)

4.2.3.2. Multiple cogeneration units. Another possibility is the use of separate cogeneration units instead of one single unit. This option is shown in Fig. 4D for three separate identical units. All units have a different role in the total heat delivery, ranging from a "base-load" cogeneration with the highest annual use and a "peak-load" unit with the lowest annual use.

The study of using different units has many optimisation parameters such as the optimisation of the number of units, the absolute and relative size of the units and the actual use of the units (i.e., aspects such as partial-heat recovery or the use of heat storage).

4.2.3.3. Cogeneration at partial load. Some cogeneration engines can be operated at partial load, possibly with a small sacrifice in overall energy conversion rates. As such, it is also possible to extend the use of the cogeneration unit. Although not stated explicitly above, all cases considered in what follows use cogeneration units that operate in on/off mode.

4.2.4. Evaluation criteria

In the following simulations, we work out different case studies for the case study of the service sector. In order to objectively weigh the results, two criteria are used. The first criterion is the absolute benefit in the form of the aggregate amount of energy saving and the emission reduction. The second criterion is the "quality" of the cogeneration. In order to determine the quality, we introduce the real "quality index" of cogeneration as follows:

$$\mathrm{QI}_{\mathrm{energy}} = \frac{\text{energy savings}}{\text{energy savings} + \text{energy use cogeneration}}, \tag{1}$$

$$\mathrm{QI}_{\mathrm{CO_2}} = \frac{\mathrm{CO_2}\text{ reduction}}{\mathrm{CO_2}\text{ reduction} + \mathrm{CO_2}\text{ emissions cogeneration}}. \tag{2}$$

The logic behind these quality indices lies in the more common definition of the quality index used in static simplified approaches where the quality index is defined as follows:

$$\mathrm{QI}_{\mathrm{STATIC}} = \frac{\text{energy savings}}{\text{energy use separate generation of heat and power}}. \tag{3}$$

Since we do not make use of the artificial reference of separate generation units, we cannot use this static quality index. However, it can be logically established that

$$\begin{aligned}&\text{primary-energy use of separate generation of heat and power}\\&\quad-\text{energy use cogeneration}\\&\quad=\text{energy savings}\end{aligned} \tag{4}$$

or that

$$\begin{aligned}&\text{primary-energy use of separate generation of heat and power}\\&\quad=\text{energy use cogeneration}+\text{energy savings}.\end{aligned} \tag{5}$$

With Eq. (5) we can transform Eq. (3) into Eq. (1) and likewise establish a corresponding QI for CO_2 in Eq. (2).

4.3. Simulation results

4.3.1. Set up

4.3.1.1. PROMIX input. In this paper, an estimate for the Belgian power system of 2010 is used to illustrate our methodological approach. We start from the composition of the existing power system and assume that the necessary new investments in the power system from now until 2010 are all combined-cycle gas-fired units. In general, this results in a 15 GW system consisting of 38% nuclear power, 26% combined-cycle gas, 20% steam-cycle power (gas, coal, oil, blast-boiler gas, coke-oven gas) and 8% cogeneration (mainly industrial applications). This is only the rough outline of the system. In total, there are over 200 different power units in the PROMIX input, all with their own specificities.

For the primary-energy prices, we use the IEA 2004 prognoses (IEA [9]) for 2010: steam coal at 40 $/tonne, natural gas at 3.3 $/MBtu and crude oil at 22 $/barrel. Expressed in $/GJ, these numbers correspond to 1.43 $/GJ for steam coal, 3.1 $/GJ for natural gas and 3.8 $/GJ for crude oil. For nuclear "fuel" we assume a price of 1.09 $/GJ.

For the hourly electricity demand, we extrapolate a historic electricity-demand profile to a total of 98.4 TW h/year.

Table 1
Simulation results of "classic" sizing of cogeneration according to the "maximum-rectangle" rule compared to the base-case scenario without additional cogeneration in the service sector

		Base case	"Maximum-rectangle" ($P_E = 315$ MW_E, $P_Q = 450$ MW_Q)
Heat demand service sector	[GWh_Q]	3950	
Power generation	[GWh_E]	95,280	
Cogeneration			
Heat generation	[GWh_Q]	–	1650
Power generation	[GWh_E]	–	1160
Primary-energy use	[PJ]	–	11.9
CO_2 emissions	[kton]	–	700
Boiler			
Heat generation	[GWh_Q]	3950	2300
Primary-energy use	[PJ]	15.82	9.21
CO_2 emissions	[kton]	927	540
Central power			
Power generation	[GWh_E]	95,280	94,120
Primary-energy use	[PJ]	821.2	814.4
CO_2 emissions	[kton]	27,560	27,160
Primary-energy savings	[PJ]		1.5
QI_{energy}	[%]		11
CO_2-emission reduction	[kton]		90
QI_{CO_2}	[%]		11

The simulation examples in this paper are performed for the specific estimated Belgian energetic context in 2010 and for the fuel-price prognoses of the IEA. These boundary conditions determine the power generation mix and the optimal dispatching strategy. Different boundary conditions will lead to different results. We merely present this example to illustrate the method, not to draw specific numerical conclusions.

4.3.1.2. Heat demand and cogeneration devices. In order to test our two possible options for optimising cogeneration sizing according to primary-energy saving or emission reduction, we perform different alternative case studies. For all case studies, we assume an overall heat demand in the service sector of 3950 GWh/a according to the chronological profile of Fig. 2. This profile has a maximum of 1630 MW h/h.

For all cases we consider cogeneration engines with full-load electric and thermal conversion rates $\alpha_E = 35\%$ and $\alpha_Q = 50\%$. According to the static evaluation, such engines would have a quality index as defined in Eq. (3) of 16% when compared to a combined-cycle power plant with a 55% efficiency and a boiler with a 90% efficiency.

In this paper, all examples have been worked out for the total service sector. The conclusions drawn from the results of these simulations are therefore only valid for this application. Every different application sector (such as industry, residential heating, tri-generation, agriculture and horticulture) or every specific application (such as the sub-sectors under the service sector: offices, education and research, hospitals, shops, hotels and catering industry, sports and culture centres or laundry services), will have its own set of results and (possibly different) conclusions.

4.3.2. Classic approach with "maximum-rectangle" rule

When using the "maximum-rectangle" rule as explained above, we can fit a cogeneration unit[2] of 450 MW_Q (and 315 MW_E) in the load-duration curve of heat demand in the service sector. This cogeneration unit generates 1650 GWh_Q of heat and 1160 GWh_E of electricity annually. Its annual use is 3670 h/a.

We assume that the 315 MW_E cogeneration prevents the installation of an equivalent amount of central power to avoid double investment. Therefore, the central power system in the "maximum-rectangle" scenario has 350 MW_E (with a reliability of 90%) less combined-cycle gas-fired units in comparison with the base-case scenario towards 2010.

The simulation results of the "maximum-rectangle" scenario and the base-case scenario without additional cogeneration in the service sector are shown in Table 1.

The bottom-line conclusion of this use of cogeneration is that it leads to an acceptable saving in primary-energy use of 1.5 PJ/a and CO_2-emission reduction of 90 kton/a.

When looking more closely at the results, we can better understand this result that is apparently less optimistic than the previously mentioned result of the static formula in Eq. (3) predicting a 16% benefit. The cogeneration unit is "only" activated during 3670 h/a. The avoided combined-cycle unit, on the other hand, would have had a higher utilisation. This "gap" has to be filled in with other, still available, generating units with a lower efficiency than the avoided combined-cycle unit.

This negative effect can be alleviated by prolonging the use of the cogeneration unit and therefore reducing the gap between the cogeneration units and the avoided combined-cycle unit. Such efforts are discussed in the following sections.

4.3.3. Reduced-scale sizing

A first possibility to prolong the annual use of cogeneration for the application in the service sector is the use of smaller cogeneration units as already discussed in Section 4.2. Here, we fully simulate three alternative cases compared to the "maximum-rectangle" rule with a rated power of 450 MW_Q for the cogeneration unit. The application of these cases in the heat demand profile is illustrated in Fig. 5.

[2] We use a fictitious aggregate cogeneration unit to represent the whole of a large number of small cogeneration units.

- In "case R75", we use a 340 MW_Q cogeneration, or 75% of the "maximum-rectangle" cogeneration. By using this smaller unit, the annual use increases from 3670 h/a to 4710 h/a. Since this sizing deviates from the "maximum-rectangle" rule, the heat generation (in energy terms) decreases from 1650 GWh_Q to 1590 GWh_Q.
- In "case R50", a 230 MW_Q cogeneration, or 50% of the "maximum-rectangle" cogeneration is used. Here, the annual use further increases to 6160 h/a and the annual heat generation further drops to 1390 GWh_Q.
- In "case R25", 25% of the "maximum-rectangle" cogeneration is used, or 110 MW_Q. The annual use is 8010 h/a with an annual heat generation of only 900 GWh_Q.

The simulation results for these three cases in comparison to the base case without additional cogeneration are shown in Fig. 6.

Both for CO_2 and primary energy, the quality indices generally increase when smaller cogeneration units are used. The QI_{energy} increases from 11% in the "maximum-rectangle" case to 16% in "case R50" and "case R25". The QI_{CO_2} increases from 11% in the "maximum-rectangle" case to almost 17% in "case R50".

Even with the decrease in overall heat and electricity generation (in energy terms) in the case of smaller cogeneration units, the quality improvement can also lead to a higher primary-energy saving and emission reduction. Fig. 6 shows that the optimal total primary-energy saving is reached near "case R50" with a total primary-energy

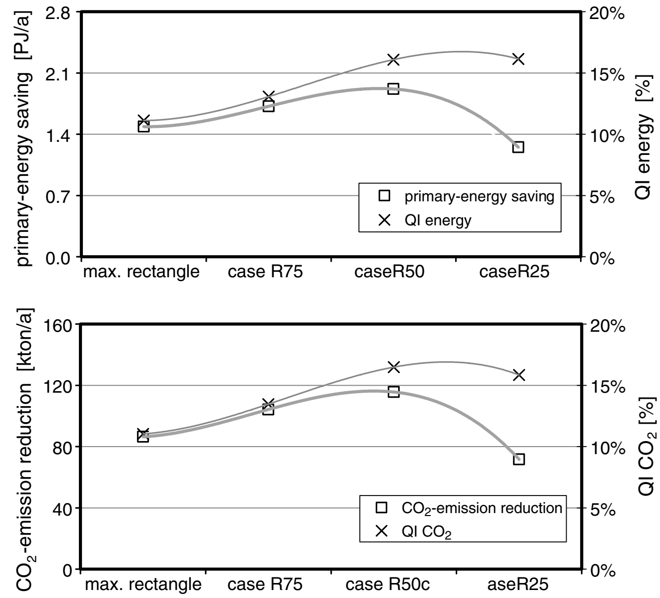

Fig. 6. Results of the scenarios with reduced-sale sizing of cogeneration compared to the results obtained by using the "maximum-rectangle" rule for cogeneration in the service sector.

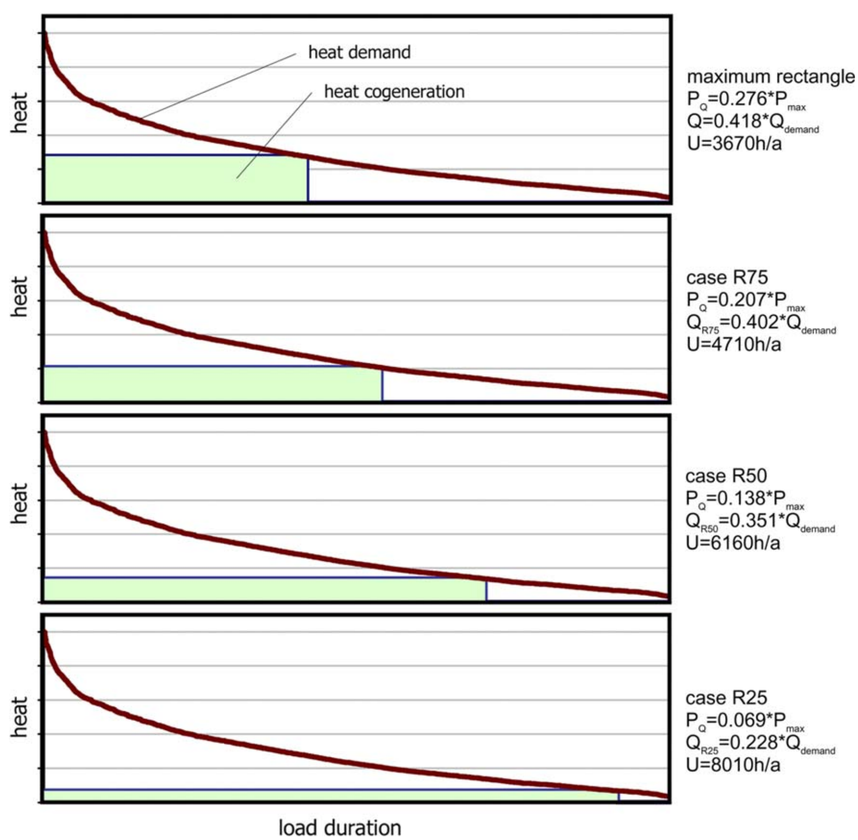

Fig. 5. Reduced-scale sizing of cogeneration. The thermal power of the three alternatives is 75%, 50% and 25% of the rated thermal power in the "maximum-rectangle" case in the top figure for case R75, case R50 and case R25, respectively.

saving of 1.9 PJ/a compared to "only" 1.5 PJ/a in the "maximum-rectangle" scenario. The total emission reduction is highest for "case R50" with 120 kton/a compared to 90 kton/a in the "maximum-rectangle" case. Smaller cogeneration units as in "case R25" still achieve a good quality but obtain lower total benefits.

4.3.3.1. Conclusion for reduced scale sizing. For the case of cogeneration in the service sector, we can conclude that reducing the scale of the cogeneration in order to increase the annual use has an unquestionable favourable result on the quality assessment of the cogeneration.

For the abatement of greenhouse-gas emissions or to reduce the primary-energy use, a maximum absolute benefit is found for cogeneration units of about 50% of the size of the size obtained by the "maximum-rectangle" rule. Reducing the size and thus also the annual generation of heat and electricity (in energy terms), leads to a better interaction with the central power system with an overall better result and higher total primary-energy savings and emission reductions.

4.3.4. Partial-heat-usage sizing

The second possibility to obtain an extended annual use of cogeneration for application in the service sector is to also use the unit during periods of lower heat demand and to "throw away" part of the heat generated by the cogeneration during these periods as discussed in Section 4.2. Now, we simulate four concrete alternative case studies and compare the results to the "maximum-rectangle" rule with rated power of 450 MW_Q cogeneration with a total annual use of 3670 h/a, electricity generation of 1160 GWh_E and heat generation of 1650 GWh_Q. The application of these cases in the heat demand profile is illustrated in Fig. 7. In all cases, the same cogeneration unit with rated power of 450 MW_Q is used.

- In "case U25", the annual use is extended to 5010 h/a. The total heat generation increases to 2260 GWh_Q of which 100 GWh_Q cannot be used.
- In "case U50", the annual use is extended to 6260 h/a. The total heat generation further increases to 2820 GWh_Q of which 340 GWh_Q is not used.

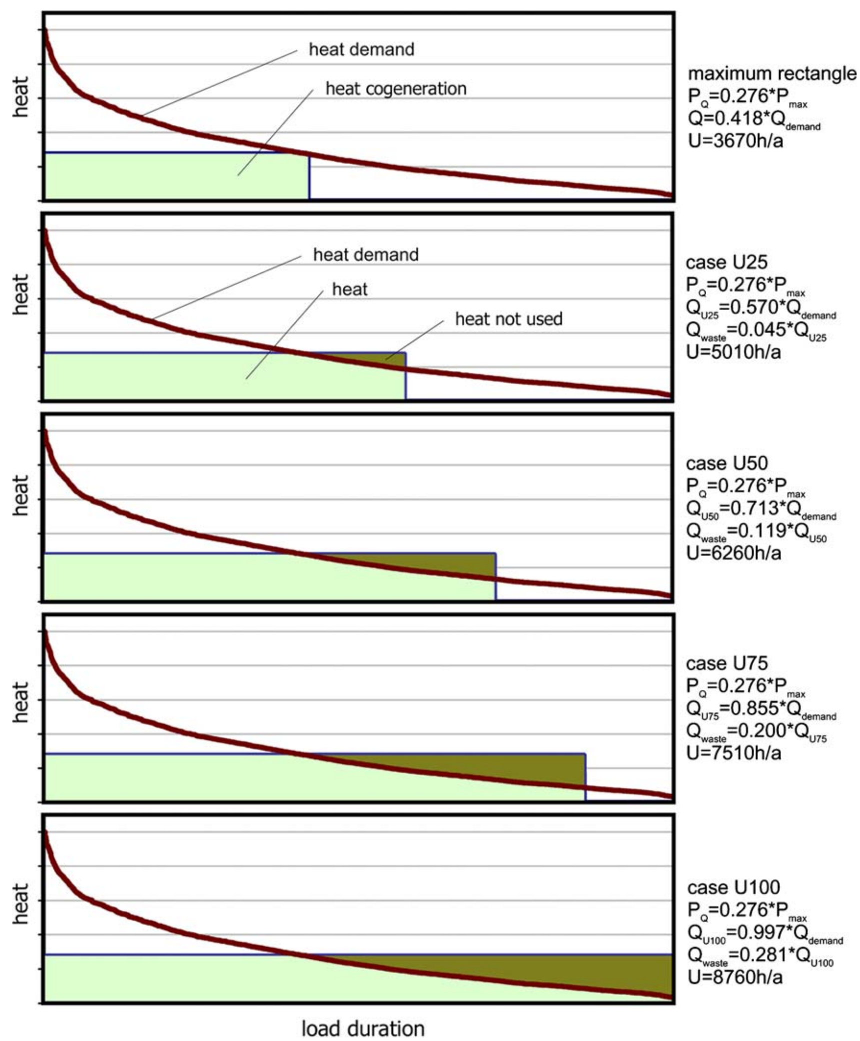

Fig. 7. Partial-heat-usage sizing of cogeneration. The annual use in the four alternative cases gradually increased from 3670 h/a in the "maximum-rectangle" case to 5010 h/a, 6260 h/a, 7510 h/a and finally the full 8760 h/a for case U25, case U50, case U75 and case U100, respectively.

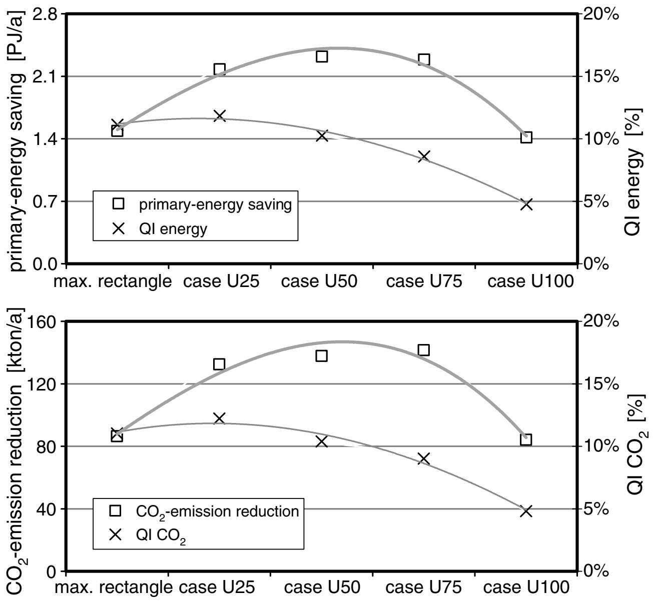

Fig. 8. Results of the scenarios with partial-heat-usage sizing of cogeneration compared to the results obtained by using the "maximum-rectangle" rule for cogeneration in the service sector.

- In "case U75", the annual use is 7510 h/a with a total heat generation of 3380 GWh_Q of which 680 GWh_Q cannot be used.
- Finally, in "case U100", the cogeneration unit is continuously operated for the full 8760 h/a. The total heat generation reaches 3940 GWh_Q of which 1110 GWh_Q is lost.

The simulation results for these cases in comparison to the base case without additional cogeneration are shown in Fig. 8.

Both for CO_2 and primary energy, the quality indices first slightly increase with increasing annual use of the cogeneration, from 11% in the "maximum-rectangle" case to 12% in "case U25". Then, the quality indices decrease to, finally, 5% in "case U100" because of the poor heat-usage rate of the cogeneration.

The total primary-energy saving and emission reduction reach an optimal value between "case U50" and "case U75" with values close to 2.3 PJ/a and 140 kton CO_2/a compared to 1.5 PJ/a and 90 kton CO_2/a in the "maximum-rectangle" case, respectively. For an even further extension of the duration use of the cogeneration unit, the benefits again decrease to 1.4 PJ/a primary-energy savings and 80 kton/a CO_2 reduction in "case U100".

4.3.4.1. Conclusion for partial-heat-usage dimesnioning. For cogeneration in the service sector, we can conclude that an extension of the use of the cogeneration units to periods of lower demand may have a favourable result of the benefits of using cogeneration, even if part of the heat is wasted.

The optimal sizing between "case U50" and "case U75", which corresponds to an extension of the annual use from 3670 h/a to about 6500 h/a, has a lower quality than the "maximum-rectangle" case but reaches higher overall primary-energy savings and emission reductions because of the better interaction with the central power system, even when about 15% of the heat generated by the cogeneration is wasted.

5. Summary and overall conclusions

In the sizing and the optimisation of the use of cogeneration, mostly static formulas are used. These simplified rules completely neglect the dynamic interaction of cogeneration with the central power system and the possibly negative effect resulting from the sub-optimal use of central power generation that has to cope with the non-dispatchable, possibly fluctuating, power generation from cogeneration.

This paper presents a simulation-based complete scenario approach in which the impact of using cogeneration can clearly and correctly be isolated. In this scenario approach, central power generation is scrupulously simulated on an hourly basis and a sub-power-plant level with the model PROMIX. One scenario is the "base case" in which no additional cogeneration is considered. Heat is delivered by boilers and all electricity comes from the central power system. In the "alternative" scenario, cogeneration is used. Heat is delivered by the cogeneration and, if necessary, by back-up boilers. The electricity generated by the cogeneration no longer needs to be provided by the central power system and is subtracted from the central demand.

Conventional sizing of cogeneration typically uses the rule that the cogeneration units can preferentially generate the largest possible share of the total heat demand with a complete utilisation of all the heat. In practice, this rule is translated as the "maximum-rectangle" rule where the largest possible rectangle is fitted inside the load-duration curve of the heat demand.

In order to improve the interaction with the central power system, we look at different possibilities where the annual use of the cogeneration can be extended. A first possibility is to use smaller cogeneration—i.e., reduced-scale sizing—that can deliver a smaller share of the heat (because the dimension deviates from the "maximum-rectangle" rule) but that can operate with a higher annual use. A second possibility considered is the extension of the use of the "maximum-rectangle" cogeneration without reducing the scale, which implies that part of the heat cannot be used. This option is called the partial-heat-usage sizing.

As an example to illustrate our method and the implications of the optimal sizing of cogeneration, we look at the possible use of cogeneration the service sector in the Belgian energetic context towards 2010.

- In the "maximum-rectangle" case, a 450 MW_Q cogeneration unit (and 315 MW_E) leads to annual primary-energy savings and CO_2-emission reduction of 1.5 PJ and 90 kton. This cogeneration has an annual use of 3670 h/a.

- The best solution in the reduced-scale scenarios has only about half the size of the ''maximum-rectangle'' cogeneration, namely 225 MW_Q with an annual use of 6160 h/a. Through the better interaction with the central power system, this cogeneration leads to higher benefits, namely primary-energy savings and CO_2-emission reduction of 1.9 PJ and 120 kton.
- The best dimension in the partial-heat-usage cases is a 450 MW_Q cogeneration unit operated for about 6500–7000 h/a. Even with heat waste rate of about 15–20%, this cogeneration manages to reach higher benefits, namely primary-energy savings and CO_2-emission reduction of 2.3 PJ and 140 kton.

We can conclude that better sizing and well-considered use of cogeneration can lead to significantly higher primary-energy savings and emission reductions than in the case of the conventional ''maximum-rectangle'' sizing.

As a caveat, we mention that the above numerical results have been obtained for the boundary conditions specified. Other compositions of central power-generation systems, other price ratios gas/coal etc., should be explored, and may lead to other results.

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