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Valuing Co-generation

The environmental effect of a large-scale co-generation plant in the Netherlands

Report

Delft, 4 May 2000

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Colophon

Library data report:
Rooijers, F.J., T.T. van der Werff; H.J. Croezen, I.S. Tellam
Valuing co-generation; The environmental effect of a large-scale co-generation plant in the Netherlands
Delft: Centre for Energy Conservation and Environmental Technology, 2000

Energy technology / Energy supply / Plant / Co-generation plant / Carbon dioxide / Emissions / Effects / Best available technologies / Capacity / Electricity / Heat / Emission reduction / Economical factors

This report costs ƒ 27,50 (€ 12,48) (excluding postage).
Publication number: 00.3730.10

Distribution of CE-publications are done by:
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Commissioned by: Rotterdam Energy Company Ltd, an affiliate of InterGen
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Summary

Rotterdam Energy Company Ltd, an affiliate of InterGen, has asked the Centre for Energy Conservation and Environmental Technology (CE) to produce a memorandum on the performance, in terms of CO_2-emissions, of the planned 800 MW_e co-generation plant (PERN10) in the Pernis (Rijnmond) area. The installation is designed to allow for the production of both low-grade heat and process steam. The plant can also be operated as a power only facility i.e., without co-generating heat. The government (on a national and provincial level) has indicated that it attaches great importance to the construction of efficient power plants as a means to combat the problem of climate change. The Netherlands has taken on responsibilities, under the Kyoto Protocol, to drastically reduce greenhouse gas emissions, including CO_2.

This report addresses a key issue commonly encountered by licensing authorities: namely how to reconcile the environmental effects of a plant installation at the local level with those on a wider, more global, basis. Accordingly, the report is structured in the following way:

- It evaluates environmental benefits of a plant at the macro (i.e. national) level (see 1 below)
- It evaluates environmental benefits at the micro (i.e. individual plant) level through a comparison of various efficiency measures (2)
- It evaluates the environmental benefits of a plant when the local (actual) situation is taken into account. (3)

1 Project Benefit Assessment at National Level – Macro view

The first part of the report addresses the impact of the plant on a national level in terms of CO_2 emissions, followed by a discussion on alternative measures.

Given the constraints of the energy supply system (variations in demand, the differences in heat and electricity demand), the effect of replacing all the existing energy plants with new ones has been investigated. To understand the impact of replacing existing plants, first the CO_2-emissions of the current energy supply system for the provision of electricity, low-grade heat and process steam have been computed. This “current situation” assumes all electricity, process steam and low-grade heat are separately generated by a mix of current technologies, such as gas-fired and coal-fired power stations, and a mix of conventional and high efficiency domestic/industrial boilers. Then, given the same demand for electricity, low-grade heat and process steam, the effect on CO_2-emissions of replacing the current situation with Best Available Technologies (BAT) has been computed. The various theoretical BAT options considered are listed below:

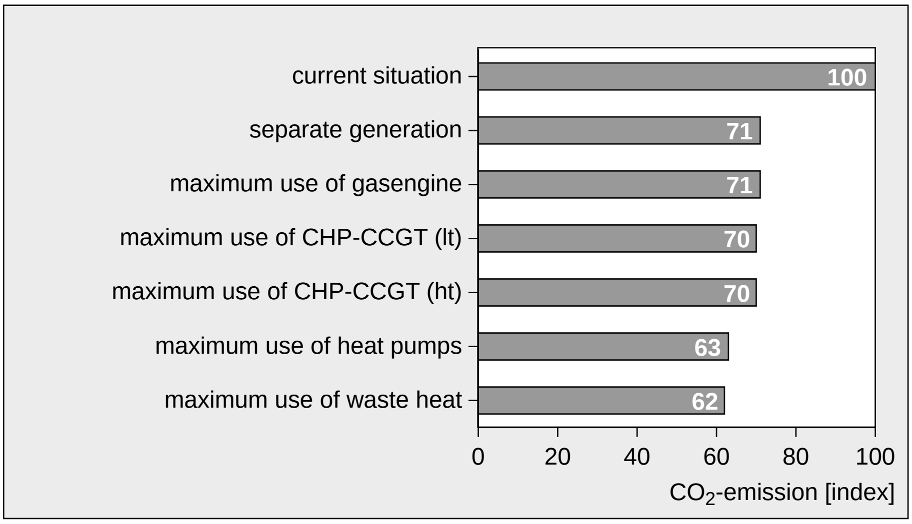
- separate generation of electricity, low-grade heat and process steam (all in BAT installations as follows: 57% electrically efficient combined cycle gas turbine power plants or ‘CCGTs’; 90% thermally efficient domestic boilers for low-grade heat; 95% thermally efficient industrial boilers for process steam);
- maximise generation of low-grade co-generated heat in small BAT gas engines. Here, given seasonal demand, these engines generate all the low grade heat and 4000 hours per year of electricity in combined heat

and power (CHP) mode; remaining electricity is generated in separate BAT; all process steam is generated in separate BAT;

- maximise generation of low-grade co-generated heat in BAT combined cycle gas turbines (CCGT). Here also, given seasonal demand, these CCGTs generate all the low grade heat and 4000 hours per year of electricity in CHP mode; remaining electricity is generated in separate (i.e. power only) BAT power plants; all process steam is generated in separate BAT industrial boilers;
- maximise supply of process steam from co-generation in BAT CCGTs. All steam and 75% electricity is produced by such CCGTs in CHP mode; 25% electricity is produced in separate BAT power plants. All low-grade heat is produced in BAT domestic boilers;
- satisfy the demand for low-grade heat by predominantly using heat pumps. In this option, 50% low-grade heat is produced by large-scale BAT heat pumps using heat from surrounding areas (e.g. surface water; waste heat from industry); 50% is produced in BAT domestic boilers. All process steam (BAT boilers) and electricity (BAT power plants) are produced separately;
- maximise use of waste heat to meet the demand for low-grade heat. 50% low-grade heat demand is satisfied by waste heat; separate BAT units are used to generate 50% low-grade heat, all process steam and all electricity.

The results of this analysis are captured in Figuur 1.

Figuur 1 CO_2-emission reduction when replacing the current situation with BAT alternative options



lt: low temperature. Refers to low-grade heat (for use in district heating)
ht: high temperature. Refers to process steam (for use in manufacturing processes)

The above chart reveals the following:

1. All the theoretical options result in major CO_2-reduction (approximately 30-35%).
2. The difference between separate generation of electricity, low-grade heat and process steam and the options that make use of co-generation is relatively small.
3. A further significant incremental CO_2-emission reduction can be achieved when using new techniques such as heat pumps and/or using industrial waste heat. However, heat pumps are currently prohibitively expensive and accessing waste heat is not always economically viable.

However, at the moment there is no incentive to use new best available technologies such as heat pumps. Therefore there is a need for national or international policy instruments (e.g. taxes, regulation, emission-trade) that make CO_2-emission reduction by these techniques economically attractive.

2 Measurements to Gauge Performance at Plant level – Micro view

The report then examines other measurements gauging environmental benefit. To analyse performance of a specific plant (at the micro level), it is necessary to apply an efficiency measurement. The following have been considered:

- "Total efficiency" (commonly used in the Netherlands) which simply adds electric and thermal efficiency at the individual plant level (i.e. "inside the fence");
- "Exergetic efficiency" which also measures efficiency at the individual plant level inside the fence, but, unlike total efficiency, accounts for the varying quality of electricity, process steam and low-grade heat;
- "Chain efficiency" which accounts not only for the quality of the various energy products, but also takes into account the transport losses in the system, beyond the fence limit of the individual plant and at the point of demand.

The environmental impact of the main plant installation in four of the six theoretical options described above is measured according to these different methods of calculating efficiency, as well as the "macro" national methodology also described above. (Heat pumps and waste heat are not discussed here, but are discussed in Chapter 3). For example, under the "maximum use of gas engine" option, the gas engine is measured; under the "large CHP-CCGT-lt" and "ht" options, the CCGT (in CHP mode) is measured. (In the separate generation option, a CCGT is the chosen installation.) They are ranked accordingly in the following matrix:

Table 1 Efficiency indicators of various systems

System			Current situation with average electricity production	separate generation	gas engine	large CHP-CCGT-lt	large CHP-CCGT-ht
Macro	Reduction in CO_2-emission	[%]	0	29	29	30	30
Micro	Total efficiency	[%]	40	57	84	82	69
	Total exergetic efficiency	[%]	36	51	37	48	51
	Electric chain efficiency	[%]	30	54	56	61	55

From the above table the following conclusions can be drawn:

1. None of the indicators on a micro level gives a good indication of the real CO_2-emission reduction as portrayed by the macro view. The macro view takes into account the ratio of the demand of electricity, low grade heat and steam and also the seasonality in energy demand.

2 'Total efficiency' is not necessarily the best indicator of the benefit to the environment, as it does not distinguish between the quality of the various energy streams. For example, the gas engine commands a high efficiency compared to separate generation, but in terms of CO_2 reduction, these are the same.
3 'Exergetic efficiency' is a more sophisticated measure of efficiency than 'total efficiency' as it distinguishes between the quality of the various energy streams. However, it still does not properly reflect the CO_2-emission reduction. For example, separate generation commands a higher efficiency over the gas engine, but in terms of CO_2 reduction, these are the same.
4 More sophisticated still is the 'chain efficiency' measure, because not only does it distinguish between the quality of the various energy streams, but it also takes into account losses that occur during transport and distribution of the energy carriers. It therefore reflects more accurately the CO_2-reduction.

3 Project Environmental Benefit – Local Level Pernis

Finally, the report examines the actual locality in which the plant is situated. A reduction in CO_2 emissions can be much more significant in the local context where the existing installations for energy production are old with below average efficiencies. This is the case locally at Pernis, where PERN 10 has the design capability to displace approximately 350 tonnes/hour for 8,000 hours/year of steam currently generated locally in existing boilers. In this situation:

1 1 The CO_2 displacement for each unit of energy demand is higher than the average displacement in the theoretical scenarios because in the local situation of Pernis it displaces steam facilities with a higher CO_2-emission per tonne steam.
2 This displacement could be potentially higher if the project could play a role in accessing waste heat currently produced by industry in Pernis and/or if the project produced low-grade heat. But there are practical problems associated with this. Gathering the waste heat within industrial sites in Pernis +-requires expensive infrastructure, which in turn requires a heat off-taker to take the risk of non-guaranteed heat supply. Similarly, a hot water pipeline from PERN 10 to customers in Rotterdam would need to be built in order to channel not only the waste heat from the refinery but any back-up hot water which may be produced from PERN 10. Though such a back-up may make it easier for a heat off-taker to bear the risk of a heat supply, the high infrastructure costs may make it difficult to sell hot water in competition with existing production sources.
3 There is a substantial reduction in CO_2 emissions even if PERN10 were operated as an electricity only facility. The benefit is however slightly lower than a 'pure' power-only CCGT, as PERN 10, in order to enable steam production, must be designed such that a small drop in electricity efficiency occurs.

Translating these displacement effects into figures, PERN10, a highly efficient plant, would result in the following potential reduction in CO_2 levels:

- of 1,600 kilotonnes(kt)/year (assuming it displaces an 800MW generator whose efficiency reflects the average of the Dutch power sector);
- of 1,900 kt/year (assuming it displaces both an average Dutch generator and 7 petajoules of domestic hot water from current producers);
- of 2,000 kt/year (assuming it displaces both an average Dutch generator and 350tph of steam for 8,000 hours currently produced locally at Pernis).

Hence, from both a national and local perspective the PERN10 project is a step in the right direction to reducing CO_2 emissions. The electricity to be produced by PERN10 has to compete on a liberalised electricity market. Who will be the competitors is hard to predict. Since PERN10 produces electricity with a very high efficiency replacement of electricity from other power plants will always result in a net decrease of CO_2-emissions.

Conclusion

1 At the **macro** level, use of BAT is the most significant step that can be taken to reduce CO_2 emissions from today's levels, whether in the form of separate generation of electricity, steam and heat, or in the form of co-generation.
2 Also at the **macro** level, there is a further significant reduction in CO_2 beyond BAT through extensive use of heat pumps and waste heat. However this is not economically feasible at the present time. National or international policy measures are therefore required to accelerate CO_2 reductions.
3 At the **micro** level, there are a number of efficiency measures which can be used to gauge energy efficiency of individual installations. None of these accurately reflect reduction in CO_2 levels, but the 'chain' efficiency measure best reflects such a reduction.
4 At the **local** level, a BAT plant such as PERN 10 can lead to considerable reductions in CO_2 where, through the delivery of 'BAT steam', it may displace much older and 'higher CO_2 emitting' facilities.

1 Introduction

Rotterdam Energy Company Ltd (an affiliate of InterGen) intends to construct an 800 MW_e natural gas-fired co-generation plant near Pernis (Rijnmond). The plant (PERN10) is designed to co-generate steam and/or heat.

Currently Rotterdam Energy Company (REC) is preparing the relevant information for the licensing procedure. These activities include carrying out an Environmental Impact Assessment (EIS). KEMA has been commissioned to prepare an EIS. The licenser, the province of South Holland, has stated that:

“The province will endeavour, under its responsibility for environmental policy in the province of South Holland and in particular the reduction of emissions of greenhouse gases, including CO_2, in the context of licensing, to strive for maximum energy efficiency. This applies particularly to energy intensive ventures. In respect of the InterGen/ENECO[1] initiative this means that with regard to the decision making process – assuming good potentials from the Pernis location in the EIS – alternatives should be elaborated which assume technical maximum heat integration with nearby industry and city heating and thereby result in a use of energy supply that is as efficient as possible”. (Province of South Holland, 1999).

Therefore, given a certain energy demand, the Province aims for minimum CO_2 emissions by aiming for maximum energy efficiency. With the introduction of increasingly efficient techniques for separated generation of heat and power, this no longer implies that co-generation installations will lead to the most energy efficient situation. In 1998 the Centre of Energy Conservation and Environmental Technology (CE) calculated that separated heat and power generation using best available technologies can increasingly compete with co-generation (Rooijers and Moorman, 1998). Also, a recent article from Van Dijen and Oude Alink (2000) supports this analysis. However, Davidse (1999) shows that in case the improvements of efficiencies of co-generation systems keep pace with the improvements of separate systems, energy savings can still be realised with co-generation systems. Obviously, as a result of the advancing development in the area of separated generation the valuation of co-generation has become more complex. REC has asked CE to assess the value of co-generation, wherein CO_2 emissions are central.

The aim of this memorandum is to reach a balanced judgement of the above mentioned activities in terms of efficiency and CO_2 emissions. Therefore the following questions are considered:

- In general, what is the contribution of a co-generation installation to CO_2 emission reduction and what are the best solutions from a macro perspective?
- In the area of Rijnmond, is there a demand for low-grade heat and/or process steam which can be satisfied in a better way by using heat and/or steam from a co-generation plant?

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[1] ENECO is a possible partner with REC in PERN10.

- What effect will the introduction of the planned co-generation plant have on Dutch CO_2 emissions? In other words, what is the potential CO_2 reduction by replacement of existing installations (steam and electricity) with PERN10?

In chapter two a method is presented which makes it possible to value co-generation installations in the context of total energy supply at a national level (macro level). Chapter three presents three methods, or indicators, which can be used to assess individual co-generation installations (micro level). The evaluation at the macro level is then compared with the measurements at the micro level to determine whether there is consistency between these measures. Chapter four takes into account the local context in the Rijnmond area. The local demand and supply for heat and process steam in the Rijnmond area are taken into account to determine the potential environmental impact of PERN10. The question of displacement of other power stations and the consequences for the environment are also addressed in this chapter. Finally, in chapter five, the overall conclusions are presented.

2 Valuation of co-generation in the macro-context

2.1 Introduction

In this chapter we present a method for valuing co-generation units, which takes account of the macro-context. Since up to now, through the use of co-generation, in many cases approximately 20% of fuel has been saved (Davidse, 1999), co-generation is generally valued positively. In practice, however, it is not sufficient to assess only the performance of individual co-generation installations. The reason for this is that the ratio in which heat and power is produced does not usually match the ratio of *demand* for heat and power. In order to reach an optimal use of co-generation units, supply and demand of both power and heat must be in tune with one another. The method described below takes account of this need for tuning.

2.2 Method

The point of departure for this method is that the valuation of energy systems must be considered in a macro context. Starting from the total demand for process steam, warm water and electricity, CO_2-emissions are calculated for various energy supply options.

The table below shows the demand in the Netherlands for electricity, low-grade heat and industrial process steam.

Table 2 Demand for various energy carriers in the Netherlands

Energy carrier	Energy demand [PJ/yr]
Electricity	200
Low-grade heat	500
Process steam	500

In order to reach an impression of optimisation at the macro level, it is useful to examine the following, sometimes extreme and unrealistic situations. For the sake of argument, the energy systems have been pushed to theoretical limits.

The assumptions behind these computations are outlined in Annexes A and C. The computations themselves are summarised in annex D.

Separate generation with existing technologies (current situation)
In this situation all electricity, all process steam and all low-grade heat are generated using separate technologies based on currently used technologies: gas-fired electric power stations; coal-fired electric power stations; industrial boilers and domestic boilers - partly high efficiency (HR), improved efficiency (VR), and conventional ones (Reference Annex C, Table 8).

Separate generation using best available technologies
In this situation all electricity, all process steam and all low-grade heat is generated using separated technologies. Only the best available technologies are used: gas fired power stations (CCGT, electrical efficiency η_e=57%), industrial boilers (η_{th}=95%) and high efficiency domestic boilers (η_{th}=90%,) (Reference Annex C, Table 9).

Maximise generation of low-grade co-generated heat in gas engines
In this situation all co-generation units are used for the production of low-grade heat. The installations are small gas engines. Low-grade heat is mainly used for heating purposes. This means that, particularly in the winter, there is a substantial demand for low-grade heat. The heating season lasts for approximately 4,000 hours. The amount of hours wherein co-generation installations operate in co-generation mode is therefore also 4,000 hours. Neglecting the difference in electric efficiency (whether operating in co-generation mode or not) and assuming furthermore that the demand for electricity is constant throughout the year, then not more than half of the electricity demand can be generated in co-generation mode. The remaining demand for electricity must then be generated separately. Further, it is assumed that all process steam is generated separately using industrial boilers. Again, in all cases, best available technologies are assumed (Reference Annex C, Table 10).

Maximise generation of low-grade co-generated heat in combined cycle gas turbines (CCGT)
In this situation all co-generation units are used for the production of low-grade heat. The difference with the previous situation is that instead of gas engines only CCGTs are used for low-grade heat production. These CCGTs operate for 4,000 hours in co-generation mode. In the remaining hours these CCGTs produce only electricity. The remaining demand for electricity is generated separately. Further, it is assumed that all process steam is generated separately using industrial boilers. Once more, in all cases, best available technologies are assumed (Reference Annex C, Table 11).

Maximise supply of process steam from co-generation in CCGT
In this situation the system is developed in such a way that the maximum possible amount of process steam is generated using co-generation units. Throughout the year the demand for process steam is more or less constant. Bearing in mind the relationship between the electrical and thermal efficiency it is possible, to generate around 75% of electricity demand using co-generation CCGTs. The remaining electricity demand is generated separately. It is further assumed that all low-grade heat is generated separately using high efficiency domestic boilers. Best available technologies are, once again, assumed in all cases (Reference Annex C, Table 12).

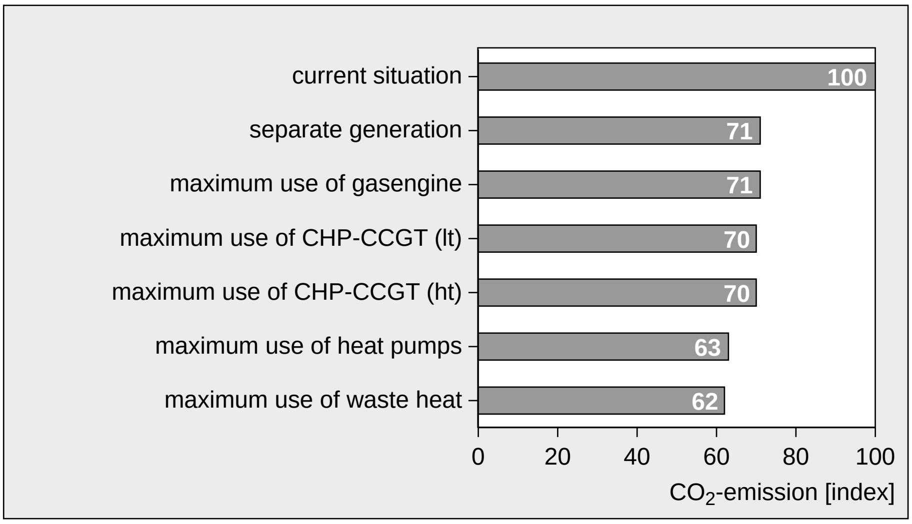
Satisfy the demand for low-grade heat by predominantly using heat pumps
In this situation 50% of the low-grade heat is produced using large-scale electric heat pumps that use heat from the surrounding area (eg. surface water, geothermal heat and waste heat from industrial processes). The remaining low-grade heat demand is generated using high efficiency domestic boilers. All electricity and all process steam is generated separately using best available technologies (Reference Annex C, Table 13).

Maximise use of waste heat to meet the demand for low-grade heat
In this situation waste heat (i.e. heat produced as a by-product of industrial processes) is used to satisfy 50% of the low-grade heat demand. The

remaining demand for low-grade heat is generated by high-efficiency domestic boilers. All electricity and all process steam are generated using the best available technologies (Reference Annex C, Table 14).

For all of these situations the CO_2 emissions are calculated for the production of electricity, process steam and low-grade heat in accordance with the demand in the Netherlands. The calculations take explicitly into account transport and distribution losses of electricity and heat. The emissions are shown in Figure 2. Technical details on the various installations can be found in annex A.

Figure 2 CO_2-emissions due to production of electricity, low-grade heat, and process steam corresponding to the Dutch energy demand



lt: low temperature. Refers to hot water for district heating;

ht: high temperature. Refers to steam used in manufacturing processes.

The following conclusions can be drawn from Figure 2:

- A large reduction in emissions is possible by replacing old installations with new ones using BAT.
- The difference between options using modern gas-fired technologies, both separated generation and generation coupled with co-generation, are relatively small.
- Among the options whereby co-generation installations are used, the delivery of low-grade heat and process steam scores the highest.
- The greatest emission reductions can be achieved by using waste heat as much as possible. However, waste heat is often produced at places where there is no or limited local demand for heat. Because of this local mismatch between supply and demand, waste heat may not be used to its full extent.
- Especially high CO_2 emission reductions can also be achieved by the use of heat pumps. In this regard it should be mentioned that the use of heat pumps has also some difficulties: the cost price is relatively high, and the supply of suitable heat sources is limited.

One has to bear in mind that the above methodology compares six situations where *best available techniques* (BAT) are applied. In reality, however, the choice is between:

- a new CHP-CCGT producing low-grade heat for domestic heating displacing existing boilers and not BAT-boilers;
- a new CHP-CCGT producing steam for industrial processes displacing existing boilers which may burn not only natural gas but also low-grade liquid fuels;
- a new CCGT producing electricity only, in which case no displacement of domestic and/or industrial boiler takes place at all.

One could argue that the installation of a co-generation plant may well lead to the displacement of domestic and/or industrial boilers that would otherwise not be displaced in the near future. Keeping all of this in mind, operating the plant in co-generation mode is to be favoured. In chapter four this issue will be addressed in more detail.

3 Alternative evaluation methods for co-generation in the micro-context

3.1 Introduction

In the previous chapter the valuation of co-generation units is placed in a macro context. In general, co-generation units are assessed on an individual (“micro”) basis. In this chapter we will examine the extent to which various individual assessment methods, or efficiency indicators, correspond to the macro-level assessment method.

3.2 Valuation on the basis of total energy efficiency

The most frequently used and simplest measure of the performance of a co-generation unit is the total efficiency of the installation in co-generation mode. In this case the electric and thermal efficiency are simply added together.

$$\eta_{\text{energetic, total}} = \eta_{\text{electric}} + \eta_{\text{thermal}}$$

Table 3 shows the total efficiency of a number of different systems. Technical data for the various systems can be found in annex A.

Table 3 Total efficiency for a number of systems

	Efficiency [%]
gas engine	84
large CHP-CCGT-lt	82
large CHP-CCGT-ht	69
heatpump	380
industrial waste heat	250
large CCGT	57

lt: low temperature. Refers to hot water for district heating;
ht: high temperature. Refers to steam used in manufacturing processes.

One drawback of this method is that there is no distinction made between thermal and electric efficiency. An installation with for example an electric efficiency of 50% and a thermal efficiency of 30% has a total efficiency equivalent to an installation with an electric efficiency of 35% and a thermal efficiency of 45% (see annex E). This method does not take sufficient account of the differences in quality between electricity, process steam and low-grade heat. The following two methods, however, do take account of these differences.

3.3 Valuation on the basis of total exergetic efficiency

The previous method makes no difference between one GJ of heat and one GJ of electricity. In fact, the value attached to electricity, steam and low-grade heat varies. This variation in value is expressed in the physical amount of ‘exergy’. The exergy of an energy carrier expresses how much work can be done when an energy carrier is brought into balance with its surroundings through an ideal process. Intuitively, it is clear that less work can be done with one GJ of water at 80°C than with the same amount of energy available in high pressure steam at 800°C. And no work at all can be done by water that is at the same temperature as its surroundings. One could say that looking at exergy prevents the overvaluation of low-grade heat.

Exergetic efficiency is defined as follows:

$$\eta_{exergetic,total} = exergy_{out}/exergy_{in}$$

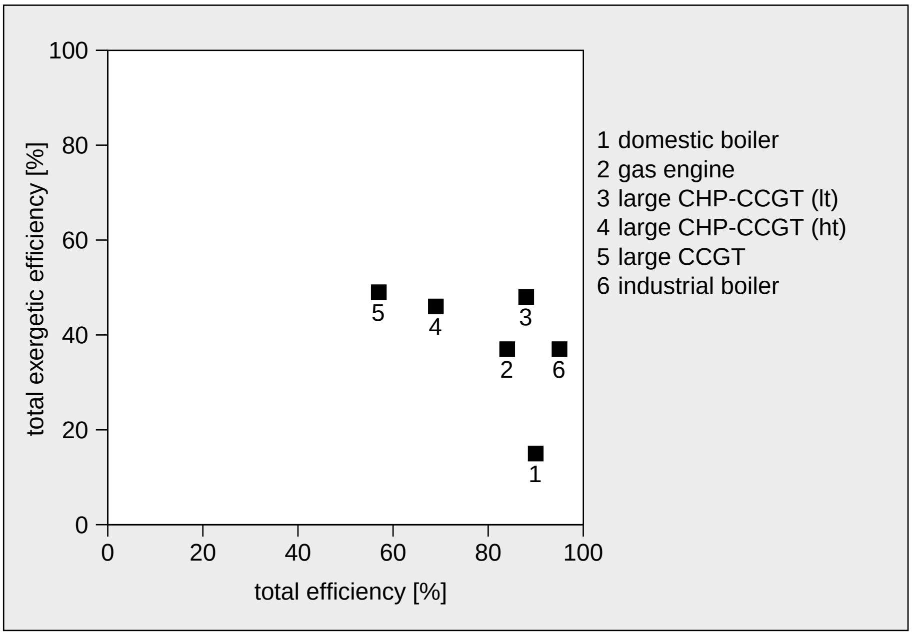
Annex B describes how exergetic efficiency is calculated. For a number of systems the total exergetic efficiency is computed. These are given in the table below.

Table 4 Total exergetic efficiency for a number of systems

	Efficiency [%]
gas engine	37
large CHP-CCGT-lt	48
large CHP-CCGT-ht	51
heatpump	65
industrial waste heat	43
large CCGT	51

lt: low temperature. Refers to hot water for district heating;
ht: high temperature. Refers to steam used in manufacturing processes.

Figure 3 Total exergetic efficiency of various co-generation systems



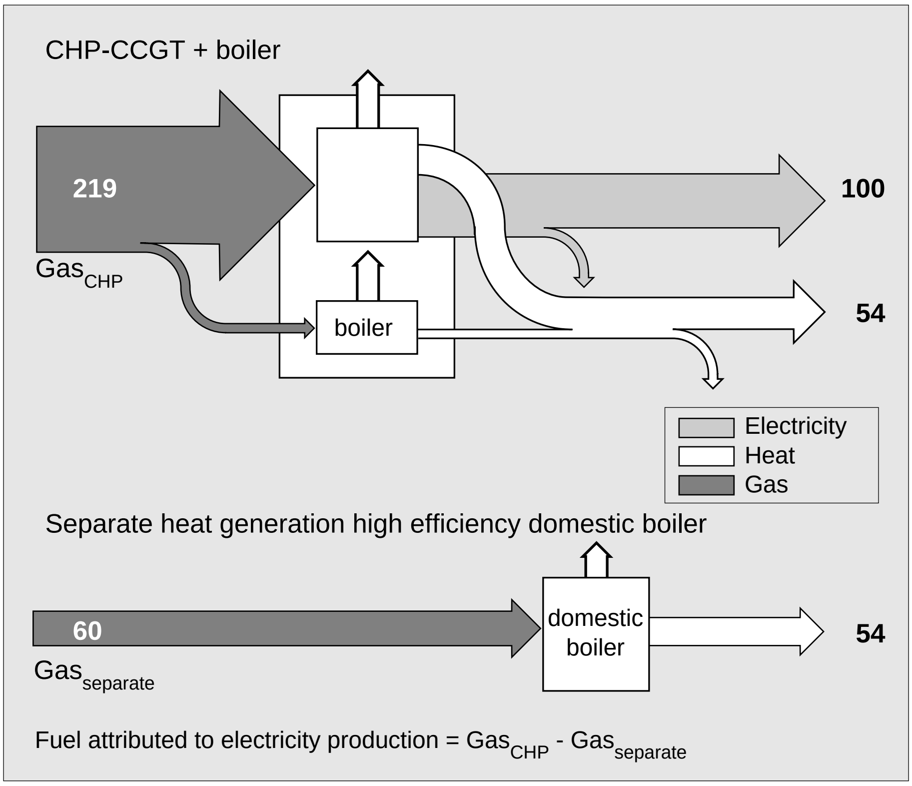
lt: low temperature. Refers to hot water for district heating;
ht: high temperature. Refers to steam used in manufacturing processes.

The figure above relates the total exergy to the total efficiency. Systems that transform a large amount of fuel into low-grade heat have relatively small exergetic efficiencies (e.g. the domestic boiler). From an exergetic point of view the stand-alone CCGT and the CHP-CCGT for the production of process steam are to be favoured.

3.4 Valuation on the basis of the amount of saved fossil fuel

This method values the amount of fuel, which is saved by a co-generation unit in relation to a reference situation. The reference system consists of the best separated generation technology. Figure 4 sketches how the amount of saved fossil energy is calculated. Note that the calculations take transport and distribution losses explicitly into account.

Figure 4 Schematic representation of co-generation and reference system for low-grade heat production



The performance of the CHP-system is expressed in terms of chain efficiency[2]. The amount of fuel that is attributed to electricity production is the total amount of fuel fed into the CHP system minus the amount of fuel fed into the domestic boiler in order to produce the same amount of heat. Depending on the comparison one has to make, the electrical or the thermal chain efficiency can be computed.

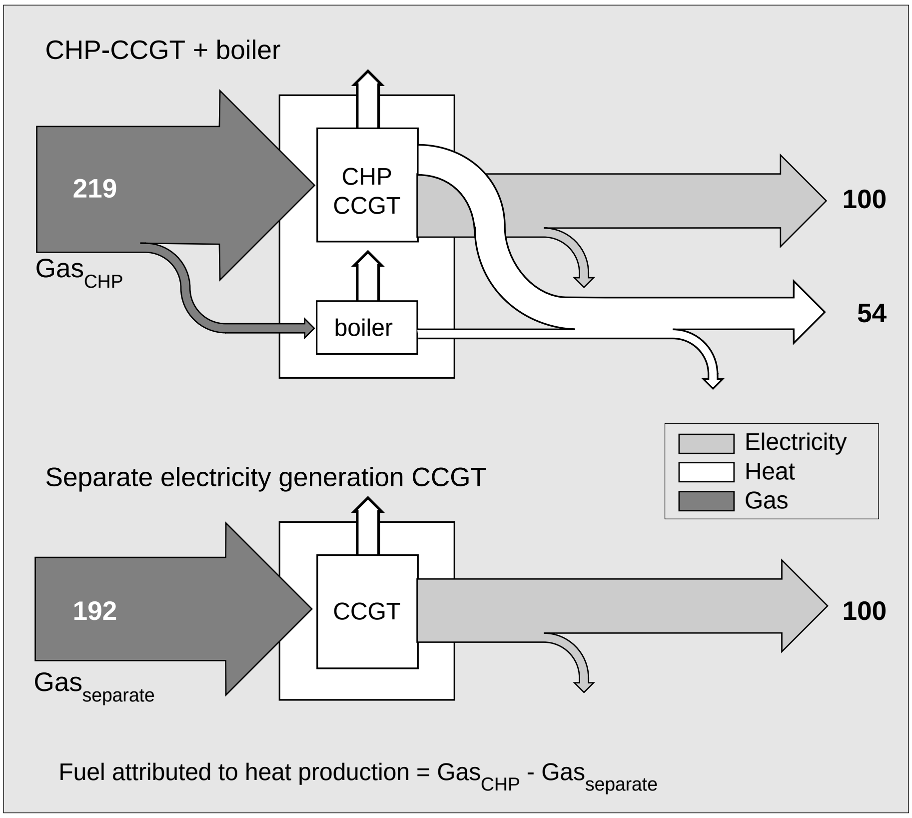
[2] The principle of chain efficiency is also used for assessing the so-called Energy Performance on Location (EPL). This is a Dutch policy instrument for computing an indicator for the environmental impact of various energy-supply systems.

The electrical chain efficiency is computed as follows:

$$\eta_{chain,\ electric} = electricity_{out}/(fuel_{CHP} - fuel_{separate})$$

Figure 5 indicates schematically the amount of fuel attributed to heat production.

Figure 5 Schematic representation of co-generation and reference system for separate electricity production



The thermal chain efficiency is computed as follows:

$$\eta_{chain,\ thermal} = heat_{out}/(fuel_{CHP} - fuel_{separate})$$

The chain-efficiencies increase with increased amounts of saved fuel. Table 5 shows the results.

Table 5 Chain-efficiencies compared to total efficiency and total exergetic efficiency for a number of systems

System		domestic boiler	gas engine	large CHP-CCGT-lt	large CHP-CCGT-ht	large CCGT	Industrial boiler	Heatpump	Waste Heat
total efficiency	[%]	90	84	82	69	57	95	380	250
total exergetic efficiency	[%]	15	37	48	51	51	37	65	43
electric chain efficiency	[%]		56	61	55	54			
thermal chain efficiency (low-grade heat)	[%]	90	61	115				152	174
thermal chain efficiency (steam)	[%]				105		95		

(Note: domestic and industrial boilers are included in the above table because, along with large CCGT, they feature in most of the theoretical options)

3.5 Conclusion

The macro method shows the contribution of specific co-generation installations to the reduction of CO_2 by assessing the demand for heat, power and steam in an integrated way. Three methods are compared with this integral method:

- total efficiency;
- total exergetic efficiency;
- chain efficiency based on saved amount of energy.

None of these three indicators gives a good indication of the real CO_2-emission reduction. The macro view gives the best indication because it takes into account the ratio of the demand of electricity, low-grade-heat and steam and also the seasonality in the energy demand.
The score, that is reached on the basis of ‘total efficiency’, does not completely match the score reached by the macro method. The reason for this is that this method does not differentiate between electric and thermal efficiency and does not take account of distribution losses. The method based on 'exergetic efficiencies' does take into account the difference in quality between electricity and heat, but does not account for distribution losses. This method values co-generation installations with a low heat-power ratio relatively better. The third method explicitly takes into account the saved amount of fuel and therefore also the avoided CO_2 emissions. Also, distribution losses are taken into account. This is why this method corresponds the best with the macro method.

In case the assessment criterion for co-generation installations is CO_2 emissions then it is best to use the macro method or the method that takes account of the saved amount of fuel (i.e. chain efficiency).

After waste heat (not available everywhere) and heat pumps (not yet technically or financially feasible) a CCGT in all three operational modes leads to a good environmental performance. The best co-generation options are those whereby low-grade heat is supplied, and the option wherein steam is supplied, followed by the option to produce only electricity (which shows a 1% increase in CO_2-emissions).

The assumption above is that low-grade heat and/or steam can be effectively used. This will be elaborated upon in the following chapter. This assumption does not count for electricity because, hypothetically speaking, in case there would be no electricity purchased, there would be no emissions.

4 Environmental impact of PERN10

PERN10 will produce mainly electricity, but will also have the capability to produce up to 350 tonnes steam per hour. It could also supply domestic hot water.

The question to be answered here is the following: how should this new CHP-CCGT-plant in the vicinity of Pernis be valued, in terms of environmental impact, taking into account the conclusions of the previous chapters and the local situation. This chapter discusses PERN10 in relation to the realities (or difficulties) in establishing a co-generation facility that maximises CO_2 reduction. It therefore draws attention to the issues that may cause PERN10 to diverge from the theoretical optimum as represented by the macro method outlined in chapter 1.

4.1 Electricity

The Dutch electricity market has recently been liberalised. In theory everyone is now able to produce and sell electricity. Large customers are free to buy their electricity from the energy company of their choice. By 2003 all consumers will probably also be free to choose their own energy company. Existing production plants are losing market to cheaper alternatives, a trend that should continue as a result of liberalisation. The plants that would lose market share would be the older and less efficient gas-fired plants, the less efficient coal plants (high operations cost) and small CHP-plants (relatively high grid costs and operations costs[3]. In addition, the liberalised market does not yet take into account the environmental impact of electricity production, but in the event that it does (for example through carbon trading) the less efficient plants and even highly efficient coal units will be further penalised.

The electricity produced by PERN10 will also have to compete in a liberalised energy market. The electricity production with PERN10 gives the best environmental performance at the moment. If the owners of PERN10 succeed in selling their electricity in the market, the net environmental impact due to electricity production will decrease by about 1,600 kt/year (see Annex F).

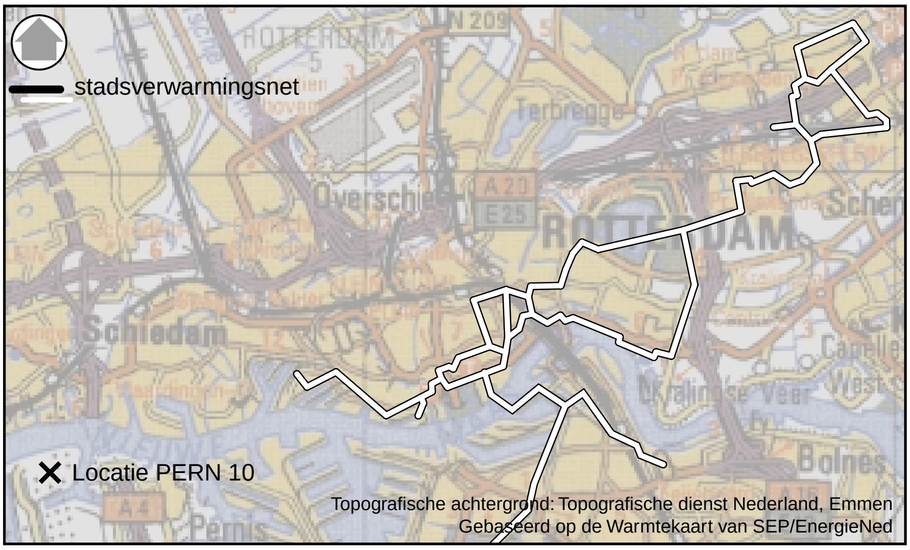
4.2 Low-grade heat demand and supply

In the area of Pernis there is a great potential for the supply of industrial waste heat, as explained in the context of the Energy 2010 project in Rijnmond. The macro-method (see chapter 1) shows that the best environmental performance, while meeting low-grade heat demand, can be achieved by utilising waste heat before sourcing heat from the operating CCGT. The practical issues associated with this are:

[3] This development corresponds with a recent analysis of ECN (Dril, 1999) concerning the future of co-generation. ECN concludes that as a result of the new gas tariffs co-generation becomes less attractive for small CHP-plants and for plants having relatively short operational times.

- Economics: Waste heat from local industry can easily be dispatched to air or to surface water. But in the local situation at Pernis, a large capital investment would be required to gather the waste heat for delivery to a single point at or near PERN10.
- Firmness of Supply: It would be very difficult for industry to guarantee a supply of waste heat which would make it equally difficult for a heat supplier such as ENECO to sign long term heat contracts with customers. PERN10 could supply back-up heat if the supply of waste heat from industry could not be guaranteed. The other back-up alternative is to produce additional heat with boilers, but from an environmental perspective the PERN10 back-up option would be a better alternative. Though such a back-up may make it easier for a heat off-taker to bear the risk of a heat supply, the off-taker must still sell hot water in competition with existing production sources and this is adversely affected if the supply is far from demand.
- Demand-Supply location mismatch: As the predominant demand centres for low-grade heat are 10-20 km away from the source, the investment required in the heat pipeline network would make it uneconomical to source low-grade heat from the Pernis area.

Figuur 6 Pernis and its surrounding area, including the current heat distribution network



Using industrial waste heat can reduce the CO_2-emission by about 500 ktonnes CO_2 per year (the assumption is a low-grade heat demand of 7 PJ/yr). Using PERN10 for the production of low-grade heat an extra CO_2-emission reduction of 300 ktonnes per year (over the 1,600 ktonnes in 4.1 above) can be reached.

4.3 Steam demand and supply

In the direct vicinity of PERN10 steam is currently produced in boilers burning low-grade liquid fuels. This results in relatively high emissions. In comparison with these current boilers every alternative using natural gas will show a better environmental performance. The difference in environmental impact between the current situation and BAT, is quite large. As has been shown in Chapter 1, the replacement with new technology results in much

lower CO_2-emissions. This also holds for PERN10, which can provide steam with much less pressure on the environment. The environmental performance of steam production with PERN10 is better than the performance of a BAT-boiler in combination with a large CCGT for electricity production.
When PERN10 produces 350 tonnes steam per hour per year an extra CO_2-emissionreduction of 400 ktonnes per year (over the 1,600 tonnes in 4.1 above) can be reached due to the displacement of the current industrial boiler.

4.4 Conclusion

A simple measure to gauge the impact of PERN10 against the theoretical options outlined in Chapter 2 would be to measure the CO_2 reduction per unit of energy demand produced by the proposed facility. The slope of this emission reduction curve is outlined in Figure 7 (highlighted against the theoretical option) and reflects a displacement of electricity and steam (currently produced in Pernis at 350 tonnes/hour, 8,000hours/year). Figure 7 highlights the following:

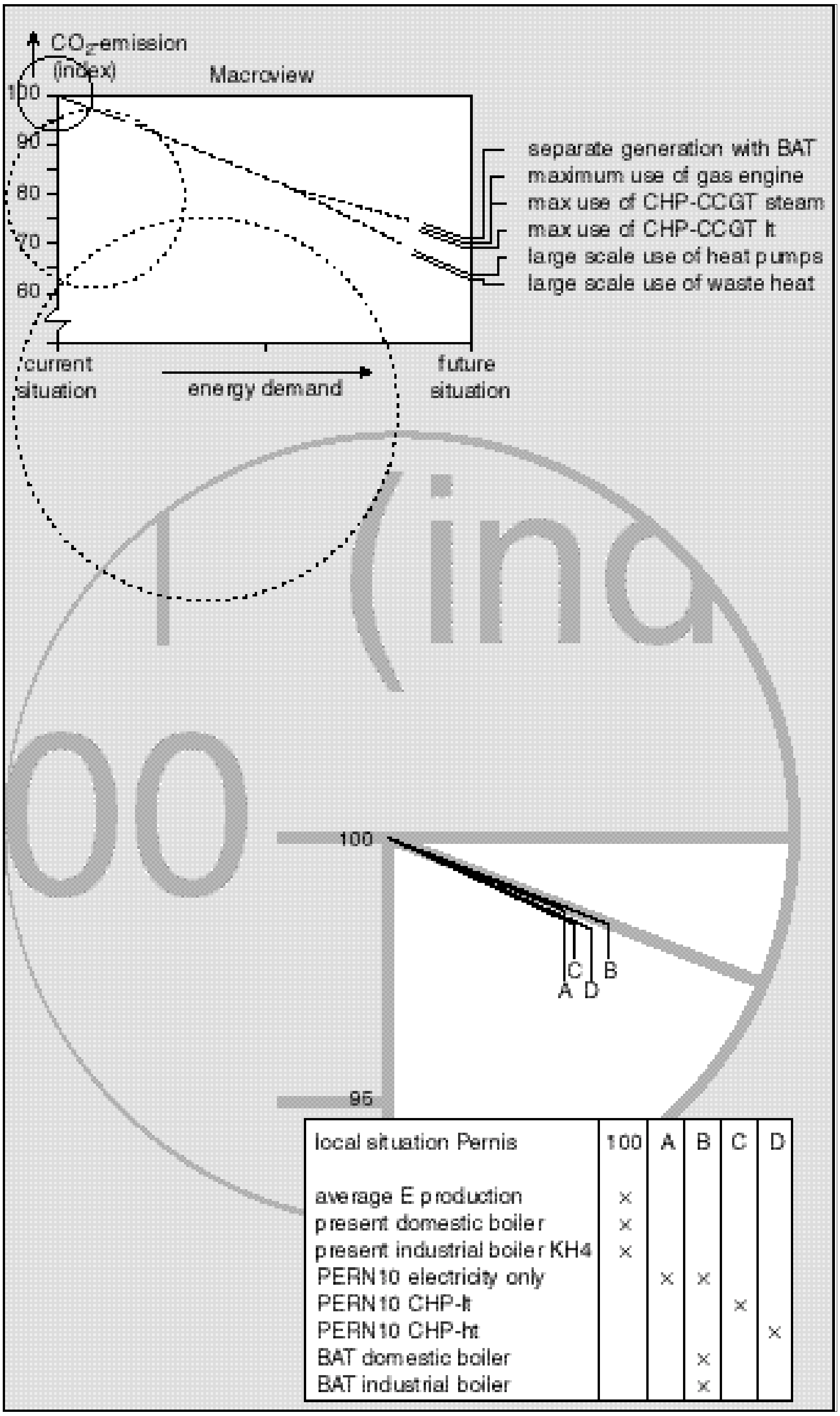
1. The CO_2 displacement for each unit energy demand is higher than the average displacement in the theoretical options because in the local situation of Pernis it displaces steam facilities with a very high CO_2-emission per tonne steam (see line D).
2. This displacement could be potentially higher if PERN10 could produce low-grade heat (line C). (Additional it could be greater if PERN 10 could access waste heat also produced by industry in Pernis.)
3. There is a substantial reduction in CO_2 emissions even if PERN10 were operated as an electricity only facility (line A and B). The benefit is however lower than a pure CCGT due to a small sacrifice in electricity efficiency to enable steam production.

In summary PERN10 is a highly efficient plant that would result in a potential reduction in CO_2 levels:

A of 1,600 kt/yr (assuming replacing an average Dutch generator);
C of 1,900 kt/yr (assuming replacing an average Dutch generator and 7 PJ domestic hot water production);
D of 2,000 kt/yr (assuming replacing an average Dutch generator and 350tph of steam for 8,000 hrs produced locally in Pernis).

Since PERN10 delivers better environmental results than the current energy supply system in all its operational modes (electric only, co-generation with low-grade heat, co-generation with steam), it delivers a (macro) reduction in CO_2 emissions. However, at the moment there is no incentive to use the best available techniques; therefore, there is a need for national or international policy instruments (e.g. taxes, regulation, emission-trading) that makes CO_2 emission reduction economically attractive.

Figure 7 Theoretical CO_2-emission reduction on a macro level due to replacement of all existing installations and (magnified) potential CO_2-reduction in the local situation of Pernis



local situation Pernis	100	A	B	C	D
average E production	×				
present domestic boiler	×				
present industrial boiler KH4	×				
PERN10 electricity only		×	×		
PERN10 CHP-lt				×	
PERN10 CHP-ht					×
BAT domestic boiler			×		
BAT industrial boiler			×		

5 Conclusions

The macro method shows the contribution of specific co-generation installations to the reduction of CO_2 by assessing the demand for heat, power and steam in an integrated way. Three methods have been compared with this integral method:

- total efficiency;
- total exergetic efficiency;
- chain efficiency based on saved amount of energy.

None of these three indicators gives a good indication of the real CO_2-emission reduction. The macro view gives the best indication because it takes into account the ratio of the demand of electricity, low-grade heat and steam and also the seasonality in the energy demand. The score, reached on the basis of total efficiency, does not completely match the score reached by the macro method. The reason for this is that the total efficiency method does not differentiate between electric and thermal efficiency and does not take account of distribution losses. The method based on exergetic efficiencies does take into account the difference in quality between electricity and heat, but not with distribution losses This method values co-generation installations with a low heat-power ratio relatively better. The third method, chain efficiency, explicitly takes into account the saved amount of fuel and therefore also the avoided CO_2 emissions. Also, distribution losses are taken into account. This is the reason that this method corresponds well with the macro method.

In case the assessment criterion for co-generation installations is CO_2 emissions then it is best to use the macro method or the method which takes account of the saved amount of fuel (i.e. chain efficiency).

After waste heat (not available everywhere) and heat pumps (not yet technically or financially feasible) the new installation in Pernis in all three operational modes leads to a good or the best environmental performance. The best co-generation options are those whereby low-grade heat is supplied, and the option wherein steam is supplied, followed by the option to produce only electricity (which shows a -1% increase in CO_2-emissions). The assumption hereby is that low-grade heat and/or steam can be effectively used.

The electricity produced by PERN10 is likely to be competitive in a liberalised energy market and will contribute to reducing emissions from the electricity sector by replacing old inefficient plants.

Earlier studies have shown that in the area around PERN10 a large amount of industrial waste heat is produced. The economics combined with demand-supply location mismatch make it infeasible to supply low-grade heat in the current context. In addition, the local situation at Pernis makes the CCGT option supplying process steam locally in Pernis the favoured one with respect to the environment.

There is a need for national or international policy instruments (e.g. taxes, regulation, emission-trading) that makes CO_2-emission reduction economically attractive. At the moment the lack of these instruments present no economic incentive for improvement of environmental performance.

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Valuing co-generation

The environmental effect of a large-scale co-generation plant in the Netherlands

Annexes

Delft, 4 May 2000

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A Technical details of installation

In this annex the efficiencies of the installations referred to in this report are given.

Table 6 Efficiencies of various installations (lt: low temperature, refers to hot water for district heating; ht: high temperature, refers to steam used in manufacturing processes)

	Installations	Reference	Present domestic boiler	Gas engine	CCGT CHP-lt	Heatpump	lt heat boiler	Solarheat	Waste heat	Present steamboiler	CCGT CHP-ht	Industrial boiler	Present electricity production	CCGT
Reference	electricity efficiency	57%												
	lt heat efficiency	90%												
	steam efficiency	95%												
Electricity (BAT)	ditribution efficiency	95%												
	transport efficiency	99%												
Low-grade heat (BAT)	efficiency CHP, electricity			31%	46%			0%	0%				40%	57%
	efficiency CHP, lt heat		80%	53%	36%	380%	90%	1500%	250%					

	Installations	Reference	Present domestict boiler	Gas engine	CCGT CHP-lt	Heatpump	lt heat boiler	Solarheat	Waste heat	Present steamboiler	CCGT CHP-ht	Industrial boiler	Present electricity production	CCGT
	efficiency CHP, full electricity			36%	54%								40%	57%
	full electricity CHP (H/y)			200	4000								8500	8500
	lt heat CHP (H/y)			4000	4000									
	heatlosses distribution			15%	15%	10%		10%	15%					
	efficiency heat transport		100%	100%	90%	100%	100%	100%	90%					
	share backup boiler			20%	10%	20%		20%	10%					
Steam (BAT)	efficiency CHP, electricity										47%			
	efficiency CHP, steam									75%	22%	95%		
	efficiency CHP, full electricity										54%			
	full electricity CHP (H/y)										0			
	steam CHP (H/y)										8000			
	efficiency steam transport									100%	90%	100%		
	share backup boiler									0%	10%	0%		

B Calculation of exergetic efficiency

The exergy of an energy carrier shows how much work can be done when the energy carrier is brought into balance with its surroundings due to an ideal process.

$$\text{Exergy} = (H - H_o) - T_o (S - S_o)$$

In which
T_o = final state temperature in degrees Kelvin
H_o = enthalpy in the final state
S_o = entropy in the final state
H = enthalpy in the first state
S = entropy in the first state

The relationship between exergy and the accompanying enthalpy is also known as *quality*.

$$\text{Quality} = \text{exergy/enthalpy}$$

The quality can reach a maximum of 1. In this case the exergy and the enthalpy in a system are equal. The quality reduces as the exergy becomes less than the enthalpy.

The table below shows the values for enthalpy, exergy and the accompanying quality for a number of systems.

Table 7 Enthalpy, exergy and quality of a number of systems

	Enthalpy [kJ/kg]	Exergy[1] [kJ/kg]	Quality
Warm water Supply = 80 oC Return = 50 oC	126	24	0.19
Steam Pressure = 18 bar Temperature = 350°C	3140	1224	0.39
Electricity	Not calculated	Not calculated	1

1) reference temperature 0°C (273°K).

The exergetic efficiency of a system can be calculated as follows

$$\eta_{exergetic} = \text{exergy}_{out}/\text{exergy}_{in}$$

or

$$\eta_{exergetic} = (\text{enthalpy}_{out} \times q_{out}) / (\text{enthalpy}_{in} \times q_{in})$$

For natural gas, q = 1, so that the efficiency of gas powered systems can be determined as follows:

$$\eta_{exergetic} = \eta_{energetic} \times q_{out}$$

For a co-generation system the total exergetic efficiency can therefore be calculated as follows:

$$\eta_{exergetic,total} = \eta_{electric} \times quality_{electricity} + \eta_{thermal} \times quality_{heat}$$

N.B. Exergetic computations are carried out by using the upper heating value of natural gas. Electric efficiencies are calculated in relation to the lower heating value of natural gas. For the exergy calculation the electric efficiency must be therefore be reduced by a factor (31,65/35,17).

For more background information see Gooi (1992).

C Fuel use in the six theoretical macro options

In this annex the theoretical options which have been introduced in chapter 1 are described in more detail. An overview is given of the amount of CO_2-emission (Mt/y) by the various systems for producing the required amount electricity, low-grade heat and process steam.

Table 8 Current situation

Supply Source	Electricity Demand (PJ/y)	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
Total	200	500	500		115

Table 9 Separate generation of electricity, low-grade heat and process steam

Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	200				21
stand alone heat lt			500		31
stand alone steam		500			29
Total	200	500	500		81

Table 10 Maximise generation of low-grade co-generated heat in gas engines

Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	100				13
stand alone heat lt			307		24
stand alone steam		500			29
CHP-lt heat	100		193		15
Total	200	500	500		81

Table 11 Maximise generation of low-grade co-generated heat in combined cycle gas turbines (CCGT)

Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	100				10
stand alone heat lt			430		27
stand alone steam		500			29
CHP-lt heat	100		70		13
Total	200	500	500		80

Table 12 Maximise supply of process steam from co-generation in CCGT

Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	50				5
stand alone heat lt			500		31
stand alone steam		426			26
CHP-steam	150	74			19
Total	200	500	500		80

Table 13 Satisfy the demand for low-grade heat by predominantly using heat pumps

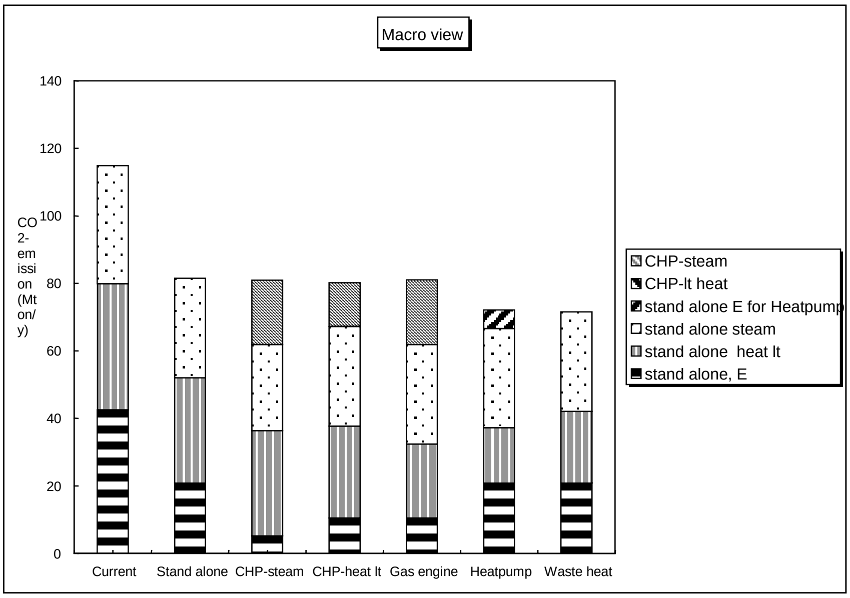
Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	200				21
stand alone heat lt			250		16
stand alone steam		500			29
heatpump			250		5
Total	200	500	500		72

Table 14 Maximise use of waste heat to meet the demand for low-grade heat

Supply Source	Electricity Demand (PJ/y	Process Steam Demand (PJ/y	Low-grade heat Demand (PJ/y		Total CO_2 (Mt/y)
stand alone, E	200				21
stand alone heat lt			250		15
stand alone steam		500			29
waste heat			250		6
Total	200	500	500		72

D Macro view

electricity demand	200	PJ/y	CE-Delft
Heatdemand lt	500	PJ/y	Frans Rooijers
Steam demand	500	PJ/y	28-apr-00



CO2-emission (Mton/y)

	Current	Stand alone	CHP-steam	CHP-heat lt	Gas engine	Heatpump	Waste heat
stand alone, E	43	21	5	10	10	21	21
stand alone heat lt	37	31	31	27	22	16	21
stand alone steam	35	29	26	29	29	29	29
stand alone E for Heatpump						5	
CHP-lt heat				13	19		
CHP-steam			19				
TOTAAL	115	81	81	80	81	72	72
% in relation to current	100%	71%	70%	70%	71%	63%	62%
% in relation to stand alone BAT	141%	100%	99%	98%	99%	89%	88%

E Comparing indicators

Table 15 highlights the performance of a CCGT producing varying quantities of low-grade heat and electricity for the macro method and the three micro methods. A clear message is that total efficiency is not a good indicator of CO_2 emissions. Thus a 70% total efficiency, when compared to the top box entitled “Total CO_2 emissions” implies a range of 51% to 74% of original CO_2 emissions. It is also clear that chain efficiency correlates highly with CO_2-emissions.

Table 15 Comparing electric and thermal efficiency (for low-grade heat delivery)

Total CO_2-emisions (indexed based on the macro-method)	horizontal = electric efficiency, vertical = thermal efficiency								
		10%	20%	30%	40%	50%	60%	70%	80%
	10%	96	69	60	55	52	51	49	48
	20%	91	66	58	54	51	50	49	
	30%	86	64	56	53	50	49		
	40%	81	61	55	51	49			
	50%	76	59	53	50				
	60%	74	56	51					
	70%	75	54						
Total efficiency	horizontal = electric efficiency, vertical = thermal efficiency								
		10%	20%	30%	40%	50%	60%	70%	80%
	10%	20	30	40	50	60	70	80	90
	20%	30	40	50	60	70	80	90	
	30%	40	50	60	70	80	90		
	40%	50	60	70	80	90			
	50%	60	70	80	90				
	60%	70	80	90					
	70%	80	90						
Exergetic efficiency	horizontal = electric efficiency, vertical = thermal efficiency								
		10%	20%	30%	40%	50%	60%	70%	80%
	10%	11	20	29	38	47	56	65	74
	20%	12	21	30	39	48	57	66	
	30%	14	23	32	41	50	59		
	40%	16	25	34	43	52			
	50%	18	27	36	45				
	60%	19	28	37					
	70%	21	30						
Chain efficiency	horizontal = electric efficiency, vertical = thermal efficiency								
		10%	20%	30%	40%	50%	60%	70%	80%
	10%	10	20	30	40	49	59	69	79
	20%	11	22	33	44	55	66	77	
	30%	12	25	37	49	62	74		
	40%	14	28	42	56	70			
	50%	16	33	49	66				
	60%	20	39	59					
	70%	24	49						

F Micro view: Location Pernis

Local situation
PERNIS

	O	A	B	C	D
average E production	X				
present boiler lt	X				
present steam boiler	X				
PERN10 electricity only		X	X		
PERN10 CHP-lt				X	
PERN10 CHP-ht					X
BAT domestic boiler			X		
BAT steam boiler			X		

	O	A	B	C	D
CO_2-emissions (index, local)	100	44	63	49	51
CO_2-emissions (index, macro)	100,00	97,46	98,32	97,68	97,78

electrical demand	[PJ/y]	22	8000
lt heat demand	[PJ/y]	7	4000
steam demand	[PJ/y]	9	8000

			" Mton CO_2/y	chain efficiency electric	lt heat	steam
average E production	[kgCO2/GJ]	177	3,901	30%		
present boiler lt	[kgCO2/GJ]	75	0,541		75%	
present steam boiler	[kgCO2/GJ]	82	0,738			80%
PERN10 electricity only	[kgCO2/GJ]	103	2,265	54%		
PERN10 CHP-lt	[kgCO2/GJ]	121	2,519	61%	115%	
PERN10 CHP-ht	[kgCO2/GJ]	119	2,627	55%		105%
BAT domestic boiler	[kgCO2/GJ]	62	0,451		90%	
BAT steam boiler	[kgCO2/GJ]	59	0,531			95%

	O	A	B	C	D
average E production	3,901				
present boiler lt	0,541				
present steam boiler	0,738				
PERN10 electricity only		2,265	2,265		
PERN10 CHP-lt				2,519	
PERN10 CHP-ht					2,627
BAT domestic boiler			0,451		
BAT steam boiler			0,531		

	O	A	B	C	D
CO_2-emissions	5,2	2,3	3,2	2,5	2,6
CO_2-emission (reference)	5,2	3,9	5,2	4,4	4,6
CO_2-reduction [Mton/y]	0,000	1,637	1,934	1,924	2,012

Local situation
PERNIS

local situation Pernis	electricity	lt heat	steam	Demand [PJ/y]	CO_2-reduction [kton/y]	[%]	
exergetic factor	0,90	0,17	0,39				
reference				0		100	O
only Eproduction	22			20	1600	98,61	A
BAT for 3 energyproducts	22	7	9	25	1900	98,35	B
CHP-lt heat	22	7		21	1900	98,35	C
CHP-steam	22		9	23	2000	98,26	D