The impact of CHP generation on CO_2 emissions

Aviel Verbruggen, Michael Wiggin, Nadine Dufait and Adwin Martens

The combined generation of heat and power (cogeneration) is praised by many as a technique for reducing the emissions of CO_2 in industrialized nations. This is generally true but not always. In this article we discuss the impact of some major variables on the CO_2 emission reduction capacity of cogeneration. Two sets of variables are predominant: the characteristics of the CHP process and the composition of the electricity generation sector. We highlight the interaction between the two sets of variables with the help of diagrams.

Keywords: Cogeneration; CO_2 emissions; Energy technologies

The combined generation of heat and power (called cogeneration or CHP (combined heat and power) is considered as a technique for saving energy and therefore also a means of reducing emissions of carbon dioxide (CO_2).[1] The latter proposition is generally true, but not in all cases. The capacity of CHP to reduce CO_2 emissions depends on several variables and it is not easy to demonstrate the relationship between CHP generation and its impact on the CO_2 balance in a simple way.

In this article we have tried to represent the impact of some major parameters in a diagrammatic way. In the first part we discuss the main variables separately and in the second part we link the variables. A short computer code has been developed to study the relationship between CO_2 emissions and CHP performance in detail. Unfortunately no simple graph can represent the relationship between CHP generation and CO_2 emissions in all its dimensions. The diagrams we present focus on the two main sets of parameters, being the CHP process itself and the electric power system competing with CHP.

Aviel Verbruggen is at the University of Antwerp, UFSIA, Prinstraat 13, B-2000, Antwerp, Belgium; Michael Wiggin is with Energy Mines and Resources, Canada; Nadine Dufait and Adwin Martens are with Vito, Belgium.

Our diagrammatic representation allows a better understanding of the interference between CHP performance and the central power generation mix. It also shows under what conditions a uniform carbon tax would or would not favour the development of CHP.

OVERVIEW OF MAIN PARAMETERS

The impact of CHP on the reduction of CO_2 emissions depends on three clusters of parameters:

- the CHP process itself;
- the heat generation process that is displaced by heat from the cogeneration process; and
- the electricity generation process that is replaced by the CHP power production.

The CHP process

A CHP process is characterized predominantly by the type of fuel it uses as an input, by its overall energy conversion efficiency and its power/heat ratio. The latter two features are easy to picture as a heat–power production possibility set in a heat–power graph.[2]

Assume that one unit of fuel (eg 1 GJ) is fed to the CHP plant. The fuel energy is converted into three types of energy: electricity, useful heat and energy losses (waste heat). Energy input equals energy output. If

x_1 = share of the fuel converted in useful heat
x_2 = share of the fuel converted in electricity
x_3 = share of the fuel lost

we obtain $x_1 + x_2 + x_3 = 1$, with $0 \leq x_i \leq 1$. The CHP process can therefore be represented as shown in Figure 1. This type of diagram is a common

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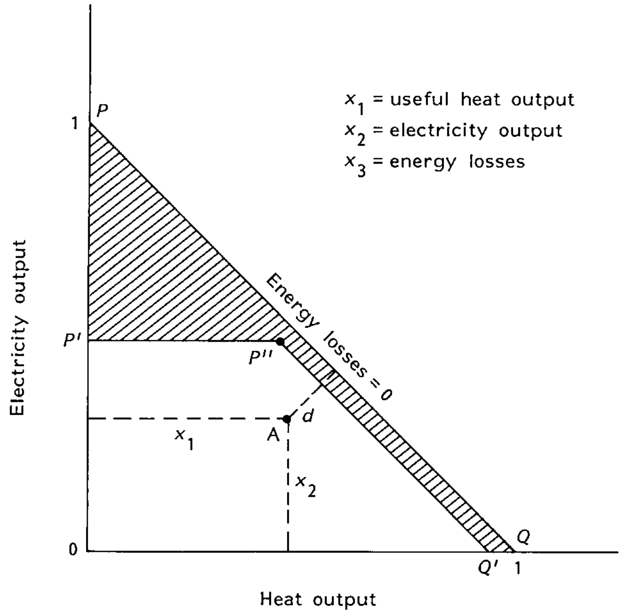

Figure 1. Energy conversion in a CHP process.[a]

Note: [a] For one unit of energy fuel input it holds that $x_1 + x_2 + x_3 = 1$, with $x_3 = \sqrt{2}\ d$.

method of representing the mathematical function $x_1 + x_2 + x_3 = 1$ in a plane and is used in probability and utility theory.[3] In Figure 1 the horizontal axis shows the heat generation efficiency of the CHP process, as does the vertical axis for power generation efficiency. All CHP processes are contained within the triangle area *OPQ* of Figure 1. The segment *PQ* represents idealized fictitious CHP processes that would occur without energy loss. The orthogonal distance *d* between any point *A* within area *OPQ* and segment *PQ* reflects the energy losses of the CHP process *A* (the geometrical distance *d* has to be multiplied by $\sqrt{2}$ in order to get the true value x_3, ensuring that $x_1 + x_2 + x_3 = 1$).

Because of physical limits, the entire area of triangle *OPQ* is not attainable by any real-life process. The polygon *OP'P"Q'* is the set of energy outputs of various feasible CHP applications. We therefore impose the approximate constraint that: $0 \leq x_2 \leq 0.5$ and $0.05 \leq x_3 \leq 1$.

The structure of Figure 1 makes it obvious that any point *A* within area *OP'P"Q'* is a one to one mapping of the heat–power ratio and of the overall conversion efficiency of a particular CHP process. To study the CO_2 emissions of CHP we have to add knowledge about the type of fuel used in the CHP process and about the carbon content of the particular fuels. By way of example we consider two types of fuels: natural gas with a CO_2 content of 52.5 kg/GJ, and coal, with 90.0 kg/GJ.

When the CHP process is fired by natural gas, 1 GJ of fuel fed to the process will give rise to the emission of 52.5 kg CO_2. Analogously, a coal fired system emits 90 kg CO_2 per GJ of fuel. These CO_2 emissions are written on the debit side of the CHP process. Whether this debit is offset by reduced CO_2 emissions elsewhere depends on the amount of electricity and useful heat cogenerated and on the properties of the separate production processes replaced by the CHP unit.

Heat generation

The useful heat output of the CHP process replaces heat from boilers fired with particular fuels and at a given efficiency. The CO_2 emissions saved by firing less fuel in the boilers can be computed when we know the type of fuel and the energy conversion efficiency of the boilers. For example, if we consider a gas fired boiler with an average efficiency of 90%, 1 GJ of net heat generated by the boiler will result in a CO_2 emission of 58.3 kg (= 52.5/0.90). Therefore 1 GJ of useful heat from the CHP process offsets 58.3 kg of CO_2.

Power generation

The electricity output of the CHP process replaces electricity from a central power system. There is a large diversity in power systems in various states depending on the availability of natural resources and on past investment policies. Here we assume that the power system makes use of three sources: coal, natural gas and a CO_2 free source (hydro or other renewable, or nuclear power).[4] Let

S_1 = share of coal in power generated
S_2 = share of natural gas
S_3 = share of CO_2 free power generation
and
$S_1 + S_2 + S_3 = 1$

It is feasible to map the three shares in a unique way in a diagram similar to Figure 1. This is shown in Figure 2, where area *ONM* represents all feasible compositions of the power generation mix with three types of sources.

To measure the CO_2 weight of any combination *B* within the feasible set *ONM*, we have to know the carbon content of the fuels used and the conversion efficiencies of the central power plants. For our further analysis, we use the assumptions shown in Table 1.

These assumptions are biased against CHP because the average efficiencies of central power generation are lower and because we do not take into

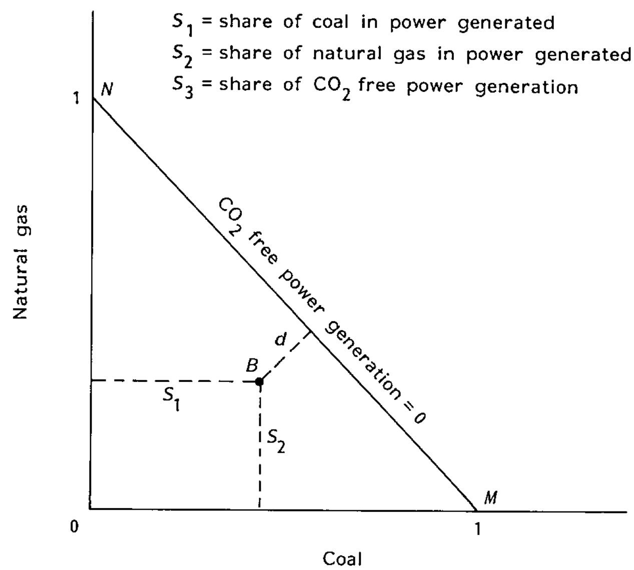

Figure 2. Fuel mix in central power generation.[a]

Note: [a] $S_3 = \sqrt{2}\ d$, in order to make graphical representation conform to the mathematical expression $S_1 + S_2 + S_3 = 1$.

account the transmission and transformation losses incurred when power has to be delivered from central stations to customer facilities. We have integrated a CO_2 free electricity source because we believe renewables will have to be developed further in the future.

CO_2 emissions avoided or added by CHP

It is straightforward to calculate the CO_2 emissions avoided or added by CHP when the actual values of the relevant parameters are known. The CO_2 debit of CHP is expressed as R_{CHP} and given by the carbon content of the fuel consumed by CHP unit eg when natural gas is fired, the CO_2 debit equals 52.5 kg CO_2/GJ $fuel_{CHP}$. The CO_2 credit of CHP is the sum of all CO_2 emissions avoided by the power and useful heat outputs of the CHP process.

The replacement effect from the useful heat output is:

$$R_{heat} = x_1 \cdot \{C_{heat}/\eta_{heat}\} \qquad (1)$$

where

x_1 = useful heat generation efficiency of CHP process (GJ heat/GJ $fuel_{CHP}$)

Table 1. Power plant efficiency.

Fuel type	Power plant efficiency kJ/kWh	(%)	Type of plant
Natural gas	7200	0.50	Combined cycles
Coal	9475	0.38	Pulverized coal

C_{heat} = carbon content of boiler fuel (kg CO_2/GJ $fuel_{boiler}$)
η_{heat} = conversion efficiency of boiler (GJ heat/ GJ $fuel_{boiler}$)

Therefore R_{heat} is given in kg CO_2/GJ $fuel_{CHP}$.

The replacement effect by the power output of the CHP process is:

$$R_{power} = x_2 \{S_1 \cdot C_{coal}/\eta_{coal} + S_2 \cdot C_{gas}/\eta_{gas}\} \qquad (2)$$

where

x_2 = power generation efficiency of CHP process (GJ power/GJ $fuel_{CHP}$)
S_1 = share of coal in central power mix (%)
S_2 = share of natural gas in central power mix (%)
C_{coal} = carbon content of coal (kg CO_2/GJ coal)
C_{gas} = carbon content of natural gas (kg CO_2/ GJ gas)
η_{coal} = efficiency of coal power plants (GJ power/ GJ coal)
η_{gas} = efficiency of natural gas power plants (GJ power/GJ gas)

Therefore R_{power} is in kg CO_2/GJ fuel $_{CHP}$. The CO_2 credit or CO_2 emissions avoided by the CHP process are the sum of $R_{heat} + R_{power}$ and given in amount of CO_2 avoided per unit of fuel fed to the CHP plant.

For simplicity we assume that the CHP process is natural gas fired and also that the separate heat boilers are gas fired units with a conversion efficiency of 90%. The power generation system is composed of three sources: CO_2 free sources, coal fired power plants ($\eta = 0.38$) and gas fired combined cycles ($\eta = 0.50$). Even when this picture does not match present reality, it may be representative of the best practice in power generation competing with CHP options. Even with these simplifying assumptions it does not seem feasible to summarize the impact of all parameters and their interdependencies in a simple diagram. Nevertheless, we propose two complementary diagrams. In the first (Figure 3) we start from a particular CHP process. In the second (Figure 5) we start from a particular central power mix. We first consider Figure 3.

The north-east quadrant of Figure 3 is a copy of Figure 2, and the south-west is a reflected copy of Figure 1. For a given CHP process (point *A* represents a CHP process where each gigajoule of gas fired provides 0.3 GJ of electricity and 0.5 GJ of useful heat, resulting in losses of 0.2 GJ), we have calculated for a number of central power generation

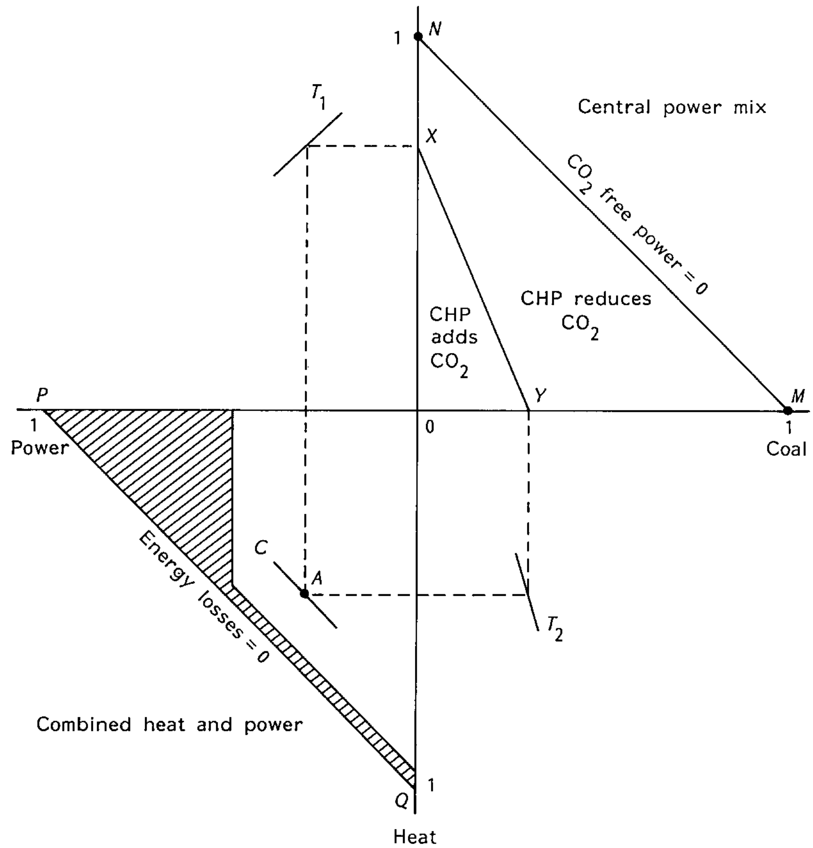

Figure 3. Reducing or increasing CO_2 by CHP, given a particular CHP process (point *A*).

compositions, the amount of CO_2 avoided or added per gigajoule of fuel supplied to the CHP unit. The results allow a division of area *ONM* in Figure 3 into a part *OXY* where there is a net addition of CO_2 by the particular CHP process and a part *XNMY* where CHP saves on CO_2 emitted.

The *XY* curve which divides the triangle *ONM* into two parts is given by:

$$R_{CHP} = R_{heat} + R_{power} \quad (3)$$

Substitution of Equations (1) and (2) into (3) gives:

$$R_{CHP} = x_1 \{C_{heat}/\eta_{heat}\} + x_2 \{S_1 \cdot C_{coal}/\eta_{coal} + S_2 \cdot C_{gas}/\eta_{gas}\} \quad (4)$$

It is obvious from Figure 3 that there must be a significant CO_2 free power share in the central plant mix in order to exhaust the CO_2 avoiding capacity of CHP. Keeping the same overall efficiency of the CHP unit but changing the power–heat ratio, eg $x_1 = 0.4$ and $x_2 = 0.4$ (moving *A* to point *C*, parallel to *PQ*), results in only a slight movement of the boundary line *XY*. It seems that the efficiency distribution between power and heat has a relatively small impact on the CO_2 balance, as opposed to eg the influence on the financial balance.

In Figure 4 the north-east quadrant of Figure 3 is repeated with the 1989 central power mixes of a sample of countries, shown in Table 2. In the countries in Table 2 power generation is based almost exclusively on coal, natural gas and CO_2 free sources (nuclear; renewables). By evaluating the power mixes in relation to the boundary line *XY* in Figure 4, it is possible to make a comparison between the five countries of the relationship of the power mix – CO_2 balance for the CHP process with electric efficiency of 30% and heat efficiency of 50%.

The public electricity system being mainly based on CO_2 free sources in France and in Belgium (nuclear and hydro in France, nuclear in Belgium), 1 GJ of natural gas fed to a CHP unit with an electric efficiency of 30% and heat efficiency of 50% results in an increase in CO_2 emissions. France is situated at a significant distance from the *XY* boundary line.

Table 2. Central power mix in selected countries (1989).

Country	Share in power (%) generated by Nuclear + renewables	Coal	Natural gas
Belgium	63.8	21.5	7.7
France	88.1	8.0	0.4
West Germany	38.2	48.3	7.9
The Netherlands	5.9	30.1	54.3
Spain	52.5	39.9	0.7

Source: United Nations, *Annual Bulletin of Electric Energy Statistics for Europe*, 1990.

The Netherlands is also located at a significant distance from the *XY* curve but in the area where CHP saves on CO_2 emitted. In this country only a limited part of electricity is supplied from nuclear plants or plants based on renewables. In West Germany and Spain, the CO_2 free power share is important (mainly nuclear in West Germany, nuclear and hydro in Spain) but coal also takes a high share. This results in a net saving of CO_2 by CHP.

The objective of Figure 4 is only to give comparative information. We should not lose sight of the following assumptions:

- boiler fired with natural gas: $\eta_{heat} = 0.9$;
- coal based central power plants: $\eta_{coal} = 0.38$;
- central power plants fired by natural gas: combined cycles with $\eta_{gas} = 0.50$.

These assumptions and therefore curve *XY* correspond to *future* best pactice in power and heat generation. An isolated statement about the *present* relationship of CO_2 balance to power mix in the countries in Table 2 is only possible if separate figures are used based on parameters which match the reality in these countries. This exercise can be carried out for Belgium. The boundary line *X′Y′* in Figure 4, just like curve *XY*, is given by Equation (4) but the variables C_{heat}, η_{coal} and η_{gas} are replaced by values characterizing Belgium in 1989:

C_{heat} = carbon content of *fuel oil* fired in industrial boiler plants
= 74 kg CO_2/GJ fuel oil

η_{coal} = average efficiency of coal based power plants in 1989
= 0.42 (having no flue gas cleaning)[5]

η_{gas} = average efficiency of natural gas fired central power plants in 1989
= 0.37[6]

The other variables have the same values as before.

Compared with the assumptions about future heat and power generation, the actual Belgian parameter values enlarge the part of triangle *ONM* where CHP saves on CO_2 emitted. Note that the Belgium 1989 central power mix is situated at the right side of the boundary line *X′Y′*. We can conclude that if electricity from the Belgian power system and heat generated in a boiler fired with fuel oil is replaced by electricity and heat produced in a natural gas based CHP process with an electric efficiency of 30% and a heat efficiency of 50%, CO_2 emissions are reduced.

A diagram similar to Figure 3 can be drawn when we assume a particular power generation mix and try to investigate whether the CHP process saves or increases CO_2 emissions. The results are shown in Figure 5. For composition *B* (coal share = 0.40; gas share = 0.20 and CO_2 free share = 0.40) we can divide the power–heat quadrant into a part where CHP avoids CO_2 and a part where CHP increases CO_2 emissions. The boundary curve *VW* is given by relationship (3). These illustrative results show that the efficiencies of power and of heat generation in a CHP process have to exceed particular levels in order for CHP to be a CO_2 saving process.

The results shown in Figures 3, 4 and 5 are only valid for the particular values used in the examples. Changing assumptions or values changes the picture. We also investigated the sensitivity of the results to variations in the main variables (the central power generation mix and the CHP process characteristics). We discovered the structure of the transformation curves in the second ie fourth quadrant of Figures 3 (T_1 and T_2) and 5 (T_3 and T_4) (see the appendix). This shows the impact of marginal changes of the independent variables on the depen-

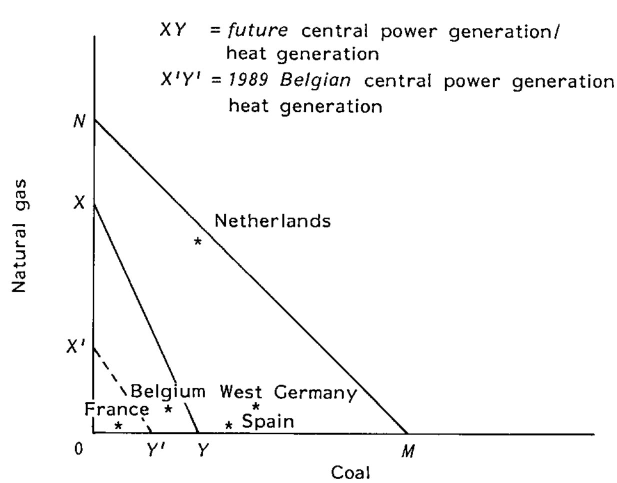

Figure 4. Reducing or increasing CO_2 by CHP in five countries, given a particular CHP process (electric efficiency = 30%; heat efficiency = 50%) and 1989 Belgian central power mix.

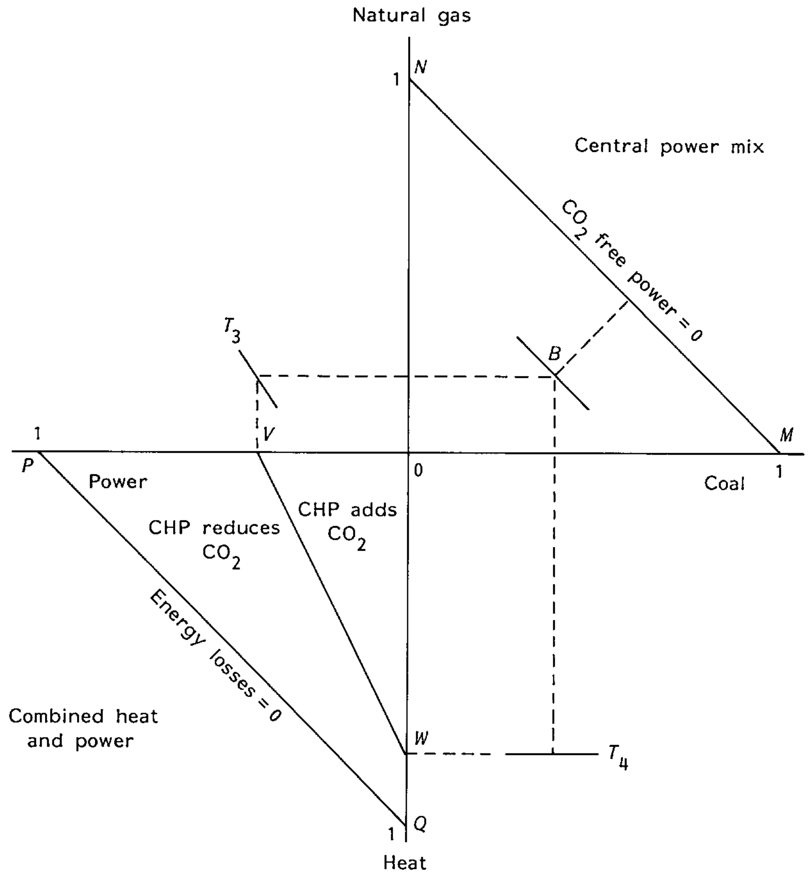

Figure 5. Reducing or increasing CO_2 by CHP, given a particular central power mix (point B).

dent variables. For example, in Figure 3, when we move point A marginally at constant overall efficiency (parallel to PQ), it is possible to obtain the corresponding XY curve in the north-east quadrant by perpendicular projection through the transformation segments T_1 and T_2. This type of information is, however, of limited use and it is better to make a new calculation of the areas for each particular CHP process or for each particular central power mix to be considered. When these calculations are carried out we also obtain cardinal information about the CO_2 emission levels instead of the purely ordinal ranking (adding/avoiding areas) of Figures 3 and 5. The merit of Figures 3 and 5 is that they provide a quick way of demonstrating the link between the quality of the CHP process and the central power mix, and the result of this link on the CO_2 balance of CHP.

CONCLUSION

The CO_2 emission impact of CHP depends on a multitude of variables and relationships that are easy to model in a computer code but not easy to represent in a simple diagram. A connection between both major groups of variables ie CHP process characteristics on the one hand, and central power generation mix on the other, has been presented diagramatically. Although our diagrams cannot offer cardinal information about CO_2 emissions, they provide a fast and ready tool for screening the CO_2 performance of CHP under various conditions.

A first application of our results is by policy makers looking at the impact of carbon taxes. When a uniform tax of say \$t/kg CO_2 is imposed on the use of fuels, our ordinal results remain valid without change (the cardinal results are now expressed in dollars instead of mass units CO_2). When different taxes are levied on the various fuels the divergence between money and carbon savings can be made obvious by superimposing one diagram on another.

[1]See eg Evan Mills, Deborah Wilson and Thomas B. Johansson 'Getting started: no regrets strategies for reducing greenhouse gas

emissions', *Energy Policy*, Vol 19, No 6, July/August 1991, pp 526–542.
[2]For a more comprehensive study of heat–power production possibilities, see eg A. Verbruggen, 'A system model of combined heat and power generation in district heating', *Resources and Energy*, February 1982.
[3]See eg M.J. Machina, 'Choice under uncertainty: problems solved and unsolved', in J.D. Hey, ed, *Current Issues in Microeconomics*, Macmillan, 1989, pp 12–46.
[4]We consider only direct emissions of energy conversion processes. A cradle-to-grave analysis would not add to our argument.
[5]BFE, *Annual Report 90*, Brussels.
[6]*Ibid.*

Appendix

Transformation curves T_1 and T_2 in Figure 3.

When the curves T_1 and T_3 in Figure 3 are known for a wider range, it is easy to obtain the boundary line XY in the north-east quadrant by perpendicular projection starting at a particular CHP process A in the south-west quadrant (Figure 3).

The curves T_1 and T_3 are derived from Equations (1) and (2) substituted in (3). This gives:

$$R_{CHP} = x_1\left(\frac{C_{heat}}{\eta_{heat}}\right) + x_2\left(S_1\frac{C_{coal}}{\eta_{coal}} + S_2\frac{C_{gas}}{\eta_{gas}}\right) \quad (4)$$

and

$$\eta_{CHP} = x_1 + x_2 \quad (5)$$

The derivation of T_1 (north-west quadrant in Figure 3) is based on $S_1 = 0$. Making use of (4) and (5) gives:

$$R_{CHP} = (\eta_{CHP} - x_2)\,\frac{C_{heat}}{\eta_{heat}} + x_2 \cdot S_2 \cdot \frac{C_{gas}}{\eta_{gas}} \quad (6)$$

or

$$T_1 = S_2 = \frac{\eta_{gas}}{C_{gas}}\left\{(R_{CHP} - \eta_{CHP})\,\frac{1}{x_2} + \frac{C_{CHP}}{\eta_{heat}}\right\} \quad (7)$$

This is the formula of a hyperbolic function.

The derivation of T_2 (south-east quadrant in Figure 3) is based on $S_2 = 0$. With (4) and (5), this leads to:

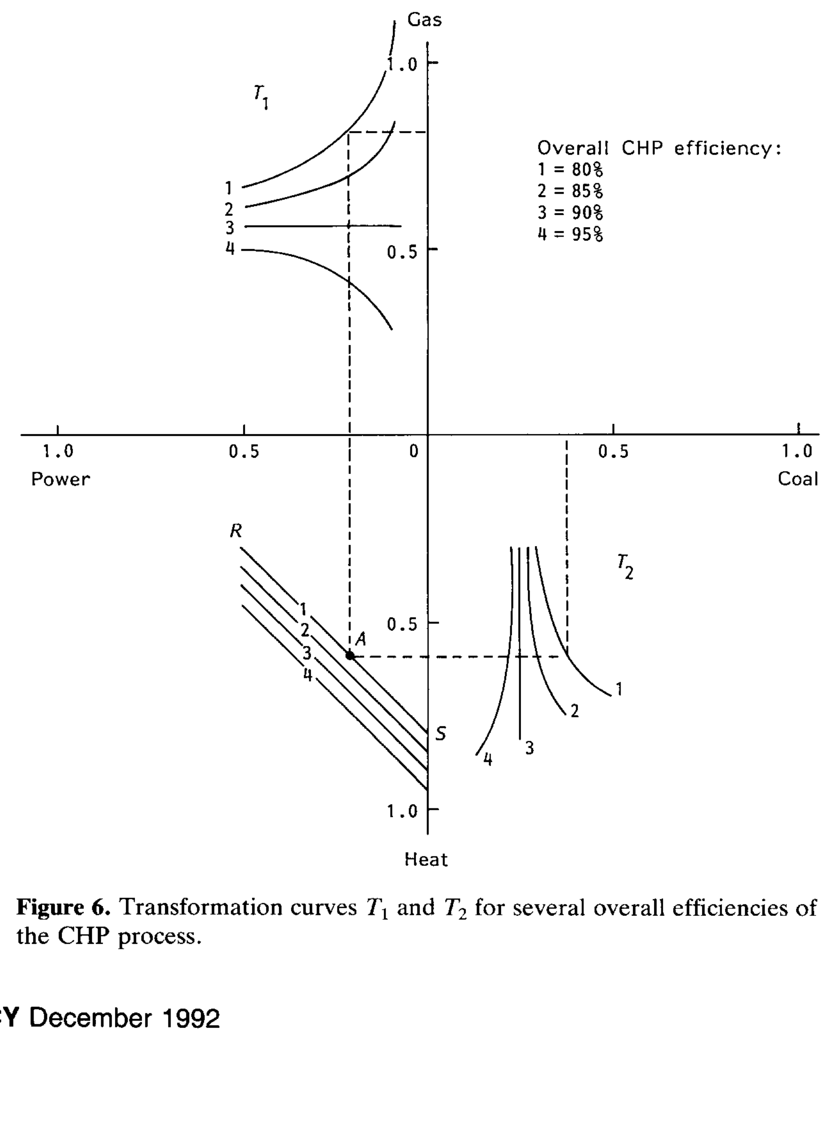

Figure 6. Transformation curves T_1 and T_2 for several overall efficiencies of the CHP process.

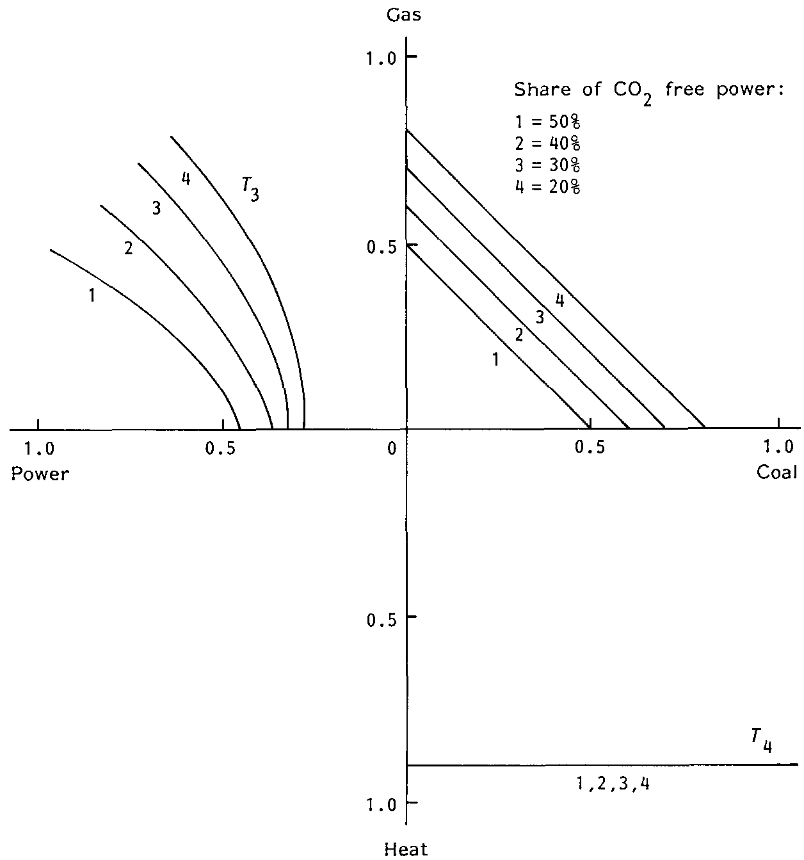

Figure 7. Transformation curves T_3 and T_4 for various central power mixes.

$$R_{CHP} = x_1\left(\frac{C_{heat}}{\eta_{heat}}\right) + \left(\eta_{CHP} - x_1\right)\left(S_1\frac{C_{coal}}{\eta_{coal}}\right) \quad (8)$$

or

$$T_2 = S_1 = \frac{\eta_{coal}}{C_{coal}}\cdot\frac{C_{heat}}{\eta_{heat}}\left\{1+\frac{\frac{\eta_{heat}}{C_{heat}}\cdot R_{CHP} - \eta_{CHP}}{\eta_{CHP} - x_1}\right\} \quad (9)$$

In order to illustrate some of these curves, we retain the figures of the text ie:

$C_{heat} = C_{gas} = R_{CHP} = 52.5$ kg CO_2/GJ
$C_{coal} = 90.0$ kg CO_2/GJ
$\eta_{heat} = 0.90$
$\eta_{gas} = 0.50$
$\eta_{coal} = 0.38$

These assumptions strongly simplify T_1 and T_2:

$$T_1\,(x_2, \eta_{CHP}) = 0.555\left[1+\frac{0.9 - \eta_{CHP}}{x_2}\right] \quad (10)$$

$$T_2\,(x_1, \eta_{CHP}) = 0.246\left[1+\frac{0.9 - \eta_{CHP}}{\eta_{CHP} - x_1}\right] \quad (11)$$

Figure 6 shows the structure of the curves T_1 and T_2 for several overall efficiencies of the CHP process η_{CHP} eg when we move point A at a constant overall efficiency (line RS) it is easy to obtain the corresponding XY curve.

Analogous to the transformation curves T_1 and T_2, the curves T_3 and T_4 were determined using Equations (4) and $S_f = S_1 + S_2$. T_3 (north-west quadrant) with $x_1 = 0$:

$$T_3 = \frac{R_{CHP}}{(S_f - S_2)\frac{C_{coal}}{\eta_{coal}} + S_2\frac{C_{gas}}{\eta_{gas}}} \quad (12)$$

T_4 (south-east quadrant), with $x_2 = 0$:

$$T_4 = \frac{R_{CHP}}{\frac{C_{heat}}{\eta_{heat}}} = \frac{R_{CHP}\cdot\eta_{heat}}{C_{heat}} \quad (13)$$

If the same numbers are used as above, the transformation curves T_3 and T_4 are:

$$T_3\,(S_2, S_f) = \frac{1}{4.5\,S_f - 2.5\,S_2} \quad (14)$$

$$T_4\,(S_1, S_f) = 0.9$$

Figures 7 shows the transformation curves T_3 and T_4.